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Forgeability Study of Medium Carbon Micro-Alloyed Forging Steel

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***Abstract*—**Micro-alloyed steel components are used in automotive industry for the necessity to make the manufacturing process cycles shorter when compared to conventional steel by eliminating heat treatment cycles, so an important saving of costs and energy can be reached by reducing the number of operations. Micro-alloying elements like vanadium, niobium or titanium have been added to medium carbon steels to achieve grain refinement with or without precipitation strengthening along with uniform microstructure throughout the matrix. Present study reports the applicability of medium carbon vanadium micro-alloyed steel in hot forging. Forgeability has been determined with respect to different cooling rates, after forging in a hydraulic press at 50% diameter reduction in temperature range of 900-1100^{0}C. Final microstructures, hardness, tensile strength, and impact strength have been evaluated. The friction coefficients of different lubricating conditions, viz., graphite in hydraulic oil, graphite in furnace oil, DF 150 (Graphite, Water-Based) die lubricant and dry or without any lubrication were obtained from the ring compression test for the above micro-alloyed steel. Results of ring compression tests indicate that graphite in hydraulic oil lubricant is preferred for free forging and dry lubricant is preferred for die forging operation. Exceptionally good forgeability and high resistance to fracture, especially for faster cooling rate has been observed for fine equiaxed ferrite-pearlite grains, some amount of bainite and fine precipitates of vanadium carbides and carbonitrides. The results indicated that the cooling rate has a remarkable effect on the microstructure and mechanical properties at room temperature.

***Keywords*—**Cooling rate, Hot forging, Micro-alloyed, Ring compression.

I. INTRODUCTION

CONVENTIONAL medium and high carbon forged steels are being widely used for several engineering applications. For example, some automobile components such as connecting rods, crankshafts, and wheel hubs can be manufactured from these steels [1]. Higher working loads and increasing demand of reliability requirements have led to an increase in the requirement of high strength and toughness in these steels. Increasing carbon as the primary alloy for higher strength and hardness of steels is usually the most economical approach to improved performance. However, some of the effects of elevated carbon levels include reduced weldability, ductility and impact toughness. In this context micro-alloyed steels have been evolved where vanadium, niobium or titanium have been added to medium carbon or low alloy steels to improve the strength through mechanism such as precipitation strengthening and grain refinement. Micro-alloyed precipitation, particularly with vanadium, can also provide temper resistance for quenched and tempered steels. High strength steels achieve the desired strength and toughness by a sequence of thermal treatments, i.e., quenching and tempering after high temperature deformation. Medium carbon microallyed steels, instead, are able to achieve high mechanical properties by a simplified thermo-mechanical treatment, based on controlled cooling after hot deformation. Consequently, the desired properties can be obtained without the separate quenching and tempering treatments required by conventional carbon steels. Eliminating separate heat treatment reduces processing cost and the machinability of the resulting ferrite+pearlite microstructure is generally superior to that of the tempered martensite at the same strength level. The yield strength and charpy impact strength are both increased by thermo-mechanically processed treatment compared to a conventionally forging schedule [2]. The strength increases due to reduction in the ferrite grain size and pearlite colony size. The reduction of the cost for the production process and the improvements in properties and performance obtainable with micro-alloyed steels therefore led to an increase in their use.

Optimization of forging process depends upon many variable but the vital parameters which can have major influence are strain rate, forging temperature, cooling rate with respect to material properties like flow stress and strength. Forging temperature plays vital role in achieving better flow stress in order to decrease the forging load with increasing die life. The cooling rate after finishing deformation stage has a significant effect on the mechanical properties. Higher cooling rates lead to a decrease of ferrite grain size and formation of high strength, hardness, dislocation density and fine phases whereas slow cooling rates lead to transformation into soft, coarse, and less dislocated phases like polygonal ferrite. Variation in the cumulative amount of deformation, working temperatures and post forging cooling rates can engender a variety of microstructure that alter significantly the mechanical properties [3]. In the metal-forming process, friction plays a significant role in determining the life of the tool, the forgeability of the material and the quality of the finished product. Excessive friction leads to heat generation, wear, pick-up and galling of the tool surface. Friction can increase the inhomogeneity of the deformation, leading to defects in the finished product. Application of a suitable

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lubricant may reduce friction, but will never eliminate it completely. To date, several methods have been developed for quantitative evaluation of friction in metal forming processes. The most accepted one for quantitative characterization of friction is to define a coefficient of friction (μ) at the die/workpiece interface, specifically, the Coulomb law of friction. Among the methods to measure the coefficient of friction, the ring compression test has gained wide acceptance in the last two decades. It was originated by [4] and later improved and presented in a usable way by [5]. The methodology consists of a simple forging operation carried on a flat ring shaped specimen. This technique utilizes the dimensional changes of a test specimen to arrive at the magnitude of the friction coefficient. For a given percentage of height reduction during compression tests, the corresponding measurement of the internal diameter of the test specimen provides a quantitative knowledge of the magnitude of the prevailing friction coefficient at the die/workpiece interface. If the specimen's internal diameter increases during the deformation, friction is low; if the specimen's internal diameter decreases during the deformation, the friction is high. This method has a particular advantage when applied to the study of friction at elevated temperatures. At high strain rates, there is no need to measure the force required to deform and no yield strength values are needed.

The present study has been carried out on aforementioned steel after a proper Thermo mechanical treatment (Forging). The role of cooling rate variation with forging temperature on the microstructure, strength and toughness has been studied to achieve an optimum combination of mechanical properties. The different mechanical properties like yield strength, ultimate tensile strength, % elongation, impact strength and hardness obtained are correlated with microstructure using high magnification optical microscope. The ring compression test has also been done to find the value of friction coefficient for different types of lubricant for that steel.

II. EXPERIMENTAL PROCEDURE

A. Test Materials

The material used in this study is the commercial grade medium carbon micro-alloyed (MC–MA) steel (38MnVS6). The chemical composition and mechanical properties of as received steel is listed in Tables I and II respectively.

TABLE I
CHEMICAL COMPOSITION OF EXPERIMENTAL 38MNVS6 MICRO-ALLOYED STEEL IN (WT. %)

C	Mn	Si	S	P	V
0.401	1.213	0.198	0.024	0.017	0.085

TABLE II
MECHANICAL PROPERTIES OF EXPERIMENTAL 38MNVS6 MICRO-ALLOYED STEEL

UTS (MPa)	YS (MPa)	%EI	Hardness (HRC)	CVN I.S. (Kg-m)
737.37	406.9	20.908	21.1	6

B. Ring Compression Test

To carry out the ring compression test, the standard ring specimen has been prepared in the ratio of OD: ID: HT: 6:3:2. The rings are compressed in between flat dies of 150 ton hydraulic press with the compression load being kept in the range 2500±500 psi. During compression maximum ram speed of the press is used to maintain same strain rate. The specimens were heated in an electric muffle furnace. The tests have been carried out at constant billet temperature of 1000 ± 50^0C and die temperature of 200 ± 50^0C. When the compression was finished the inner diameter of the ring was measured before the specimen was removed from the platens. An average value has been taken from three measurements from three arbitrary angles across the centre of the ring. In ring compression tests, the dimension of the rings has been selected as follows: OD: 45 mm; ID: 22.5 mm and Height: 15 mm as shown in Fig. 1.

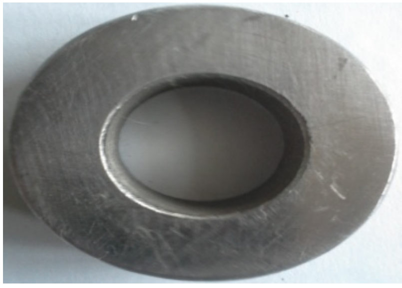


Fig. 1 A sample ring specimen

The empirical formula of [6] is used to determine coefficient of friction under sliding friction condition:

$$(\mu) = 0.055 \exp X \left(\frac{\Delta D}{\exp(0.044 X\, \Delta h + 1.06)}\right) \tag{1}$$

where μ is the coefficient of friction, ΔD is the percentage decrease in internal diameter of the specimen and Δh is the percentage reduction in height due to compression. The die lubrication conditions were as follows: (a) dry or without any lubrication; (b) graphite powder in hydraulic oil and (c) graphite powder in furnace oil (d) DF 150 (1:20) (Graphite, Water-Based) Die Lubricant. The rings were upset to different reductions ranging from 10 to 50%. A set of flat dies has been used to deform the specimens. Measurements of different dimensions of rings have been taken after the rings were cooled to room temperature by water quenching.

C. Hot Forging Test

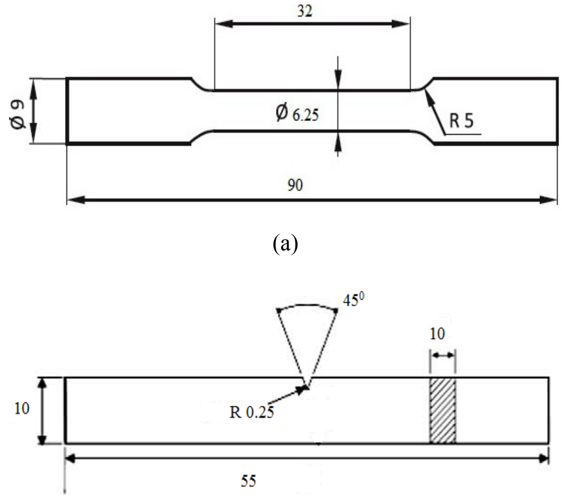
Prior to the hot forging the specimens have prepared for required size by a power hack saw machine. All forgings have been completed by using cylindrical compression testing equipment with specimen geometry, 60 mm diameter by 90 mm long given in Fig. 2. Both opposite surfaces of the specimen were parallel to ensure uniform deformation during testing. All the specimens were heated in an electrically heated muffle furnace at three different temperatures of 900^0C, 1000^0C and 1100^0C for 30 minutes. The samples have been forged in a 150 Ton hydraulic press with 50% reduction of diameter as shown in Fig. 3. Three to four times heating were required during the process of forging to get the required reduction. The forged steel samples have been cooled in normal air, forced air and quenching oil respectively.

Fig. 2 Sample prepared; D= 60 & H= 90 mm

Fig. 3 Sample after 50% diameter reduction

D. Mechanical Testing and Microstructure

Tensile and Impact toughness strength specimens have been prepared from as forged bars. Tensile strength and impact toughness strength value has measured at room temperature according to the standard on a Universal tensile-testing machine (INSTRON 1195) at a crosshead speed of 2 mm/min and in a dynamic fracture toughness testing machine (M/S Tinius Olsen, USA). Tensile test and impact test specimens were manufactured in accordance with the standard of ASTM A 370-05 [7] as shown in Figs. 4 (a) and (b). The gauge portion of the specimens was polished with fine emery paper and subsequently with 0.3μm diamond paper. Hardness measurements were also carried out using the Vickers hardness test with a 1 kg load and a diamond square-based pyramid, which gives geometrically similar impression under load. A minimum of 5 hardness measurements was made on each specimen to obtain satisfactory statistical reliability. The mechanical testing results are tabulated in Table III. Samples for microstructure were obtained from the grip portion of the tested tensile specimens. The optical microstructure has observed and shown in Fig. 7 using optical microscope. The specimens were polished according to standard metallographic methods for optical microscopy observations.



(a)

(b)

Fig. 4 Test specimen, All dimensions are in mm (a) tensile test specimen (b) Charpy V- Notch Impact test specimen

III. RESULTS AND DISCUSSION

As per the experiment conducted, the decrease in hole diameter as a function of the amount of deformation has been determined for the specimens when compressed under the said lubrication conditions. On a ring test, a ring, with outer and inner radius, is compressed. Because the inner radius is more sensitive to the friction, the inner diameter of the ring increases in the same manner as a solid section when the friction coefficient is low, whilst the inner diameter of the ring would decrease when the friction coefficient exceeds a critical value, as seen in Fig. 5, which shows the deformed rings for different lubricating conditions at different height reductions (10%, 20%, 30%, 40% and 50%) from the experiments. It is observed that the coefficient of friction (μ) is lowest in the steel with Hydraulic Oil+ Graphite condition. Based on the μ values of Steel, the Hydraulic Oil+ Graphite lubrication condition is suitable for free forging and dry lubrication condition is preferred for deep drawing and die forging operations.

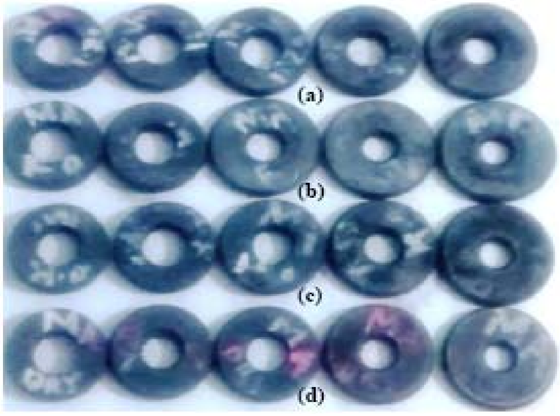


Fig. 5 Macrographs of samples deformed at 10%, 20%, 30%, 40% and 50% height reduction (a) Hydraulic Oil+ Graphite (b) Furnace Oil+ Graphite (c) DF-150 and (d) Dry

The measurements of the inner diameter and height of the specimens after ring compression tests are given in Table III and the calibration curve are plotted in Fig. 6.

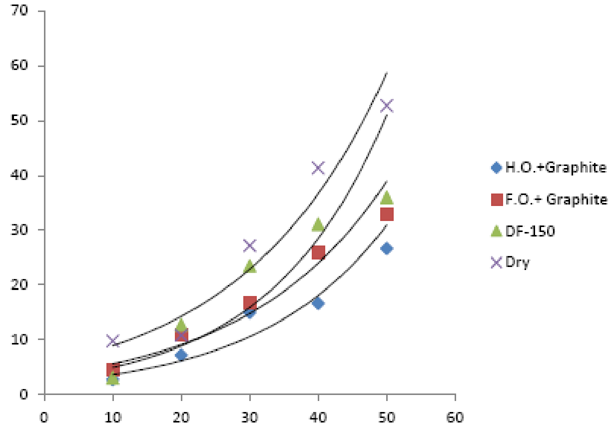


Fig. 6 Experimental friction calibration curves in terms of μ

Data shown in Table IV for ultimate tensile strength (UTS), yield strength (YS), percentage elongation (%EI), hardness (HV) and Charpy V- notch impact strength (CVN I.S.) with respect to different forging temperatures can be compared for normal air cool (NMA), forced air cool (FMA) and oil quenched (QMA) micro-alloyed steel.

TABLE III
RING COMPRESSION TEST RESULTS OF 38MNVS6 MICRO-ALLOYED STEEL AT 1000^{0}C (LUBRICATING CONDITIONS)

Lubricant	Δh (%)	ΔD(%) mean	Friction Coefficient (μ)	Average (μ)
Hydraulic Oil + Graphite (2:1)	10	2.78	0.102	0.156
	20	7.22	0.155	
	30	15	0.22	
	40	16.67	0.148	
	50	26.67	0.153	0.225
Furnace Oil + Graphite (2:1)	10	4.58	0.153	
	20	10.83	0.261	
	30	16.8	0.260	
	40	25.97	0.256	
	50	33.05	0.195	0.302
DF 150 (1:20) (Graphite, Water-Based) Die Lubricant	10	3.055	0.108	
	20	12.78	0.345	
	30	23.52	0.485	
	40	31.11	0.351	
	50	35.97	0.219	
Dry	10	9.79	0.486	0.489
	20	10.85	0.216	
	30	27.2	0.682	
	40	41.37	0.645	
	50	52.74	0.416	

TABLE IV
MECHANICAL PROPERTIES OF 38MNVS6 MICRO-ALLOYED FORGED SAMPLES

Exp. No.	Forging Temp. (^{O}C)	Cooling Condition	YS (MPa)	UTS (MPa)	% EI	Hardness (HV)	CVN I.S. (Kg-m)
1	900	NMA	524.4	762.7	22.09	263	10.7
2	900	FMA	524.9	804.3	20.02	265	9.8
3	900	QMA	567.8	817.8	19.36	275	8.9
4	1000	NMA	475.3	770.2	22.67	247	10.95
5	1000	FMA	494.8	795.3	22.48	265	8.1
6	1000	QMA	531.6	799.8	19.94	275	6.2
7	1100	NMA	437.8	797.5	20.82	259	7.2
8	1100	FMA	552.9	804.6	19.67	278	7
9	1100	QMA	559.3	811.6	15.3	298	4.3

The evaluations of the microstructure for 38MnVS6 micro-alloyed forged steel under various cooling conditions are shown in Fig. 7. Micro structural analysis indicates that NMA and FMA consist of ferrite-pearlite structure but QMA additionally contains some amount of bainite, alloyed cementite, vanadium carbides or carbo-nitrides. It has been observed that fine vanadium carbides or carbo-nitrides are distributed throughout the matrix of NMA, FMA and QMA steels. It may be predicted that tensile strength and toughness increases due to the presence of fine carbides or nitrides in the matrix of uniformly distributed fine grain structure. Hardness increases due to presence of redistribution of alloyed cementite and distribution of fine vanadium carbides or carbo-nitrides. Tensile properties of forged steels followed by different cooling rates are shown in Table IV. The yield strengths and tensile strengths are increased with increase of the cooling rates. The elongation and impact strength tends to improve at lower cooling rates such as air cooling. However, increasing the cooling rate has a negative effect on elongation and impact strength. It may be predicted that the distance that the atoms are able to diffuse is reduced during higher cooling rate and at the same time flow of grain is restricted by the harder constituent like carbides or nitrides in the matrix. The strength of the alloy is increased due to fine pearlite and uniform distribution of alloyed cementite. The hardness measurement indicated that QMA samples of steels had higher Vickers hardness compared to NMA and FMA cooled samples. This is because of the presence of bainite in the matrix. Fast cooling rate was anticipated to give a fine dispersion of small particles of alloyed carbides in the pro-eutectoid ferrite and pearlite which make dislocation movement more difficult and increase hardness. Percentage of elongation in the QMA steel has restricted due to presence of more upper bainite as when compared with FMA or NMA steels.

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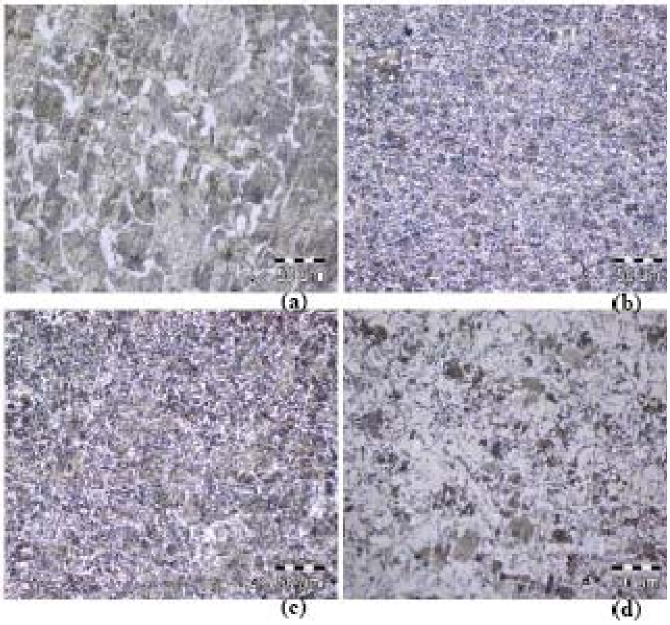

Fig. 7 Microstructures of 38MnVS6 Micro-Alloyed steel under conditions of (a) As-Received (b) NMA (c) FMA and (d) QMA.

IV. CONCLUSION

- Evaluation of coefficient of friction (μ) values through ring compression test indicate that Hydraulic Oil+ Graphite lubrication condition is suitable for free forging where as dry lubrication condition is preferable for deep drawing and close die forging operations.
- The yield strength, tensile strength and hardness have increased with increase of cooling rates. The elongation and impact strength tends to improve at slower cooling rates such as air cooling. However increasing the cooling rate has a negative effect on elongation.
- Tensile strength and Impact strength increases due to the presence of uniformly fine carbides or nitrides in the matrix of uniformly distributed fine grain structure. Hardness increases due to presence of redistribution of alloyed cementite and distribution of fine vanadium carbides or carbo-nitrides.

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