Materials and Design 51 (2013) 819–825

Contents lists available at SciVerse ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

Technical Report

Investigation on the behaviour of medium carbon and vanadium microalloyed steels by hot forging test

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ARTICLE INFO

Article history:
Received 26 March 2013
Accepted 30 April 2013
Available online 13 May 2013

ABSTRACT

Two medium carbon steel grades were used in the present investigation. One of them was microalloyed with vanadium. Both steel grades were subjected to a controlled closed die forging followed by cooling in sand, air or oil mediums. Final microstructures and mechanical properties were evaluated by optical microscopy, scanning electron microscopy, hardness and tensile tests. The results indicated that the microstructures of all close die forging and cooling conditions are dominated by ferrite and pearlite phases with different morphologies and grain sizes according to both chemical composition and cooling rate. Oil quenching leads to a formation of relatively fine ferrite and pearlite in medium carbon steel (MC) or martensite in medium carbon microalloyed steel (MC–MA). Relatively fine ferrite, pearlite and martensite increase strength but decrease ductility. The cooling rate has a remarkable effect on the microstructure and mechanical properties at room temperature.

1. Introduction

Medium carbon steel (MC, AISI 1040) and medium carbon microalloyed steel (MC–MA, 38MnVS6) are being widely used for machinery structural parts [1]. In particular, MC–MA steels do not require heat treatment after they are shaped into parts, as the mechanical properties are obtained directly at the end of the process, so an important saving of costs and energy can be reached by reducing the number of operations. Also, these steels present very good characteristics of toughness and weldability. These beneficial properties have been achieved by a careful control of chemical composition and by adopting suitably controlled thermo-mechanical processes [2]. During hot working of plain carbon steels, the microstructure development is not as pronounced, as can be observed in the case of microalloyed steels that contain small amounts of Ti, Nb, Al or V singly or in combination [3].

In recent years, many papers demonstrated that microalloyed steels, containing 0.30–0.50 wt.% of C, could satisfactorily replace conventional quenched and tempered steels. The driving force behind the development of microalloyed steels has been the need to reduce manufacturing costs. High strength steels achieve the desired strength and toughness by a sequence of thermal treatments, i.e., quenching and tempering after high temperature deformation. MC–MA steels, instead, are able to achieve high mechanical properties thanks to 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. The reduction of the cost for the production process and the improvements in properties and performance obtainable with microalloyed steels therefore led to an increase in their use [4,5].

The addition of alloying elements offers an important cost-effective approach to obtain a good combination of excellent toughness and strength through grain size control and precipitation hardening [6,7]. In microalloyed steels, strength increases are primarily achieved through increase of the pearlite volume fraction or by grain refinement and precipitation strengthening of the ferrite matrix as controlled with microalloy additions (e.g., Ti, Nb, or Al for grain size control and V for precipitation strengthening) [8]. However, hot deformation is an important parameter in grain refinement as well as microalloying elements. Rough deformation in austenite recrystallization region refines coarse austenite grains by repeated deformation and recrystallization. However, deformation in non-recrystallization region increases ferrite nucleation sites through pancaking of austenite grains and creation of deformation bands [9,10]. In this way, fine ferrite grains structure will be produced after transformation. These achievements are maintained when higher cooling rates are applied. Among hot deformation

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http://dx.doi.org/10.1016/j.matdes.2013.04.102

processes, forging has become a competitive technique for processing such steels [11,12].

The cooling rate after finishing deformation stage has a significant effect on the mechanical properties through engendering a variety of microstructure constituents that alter significantly the mechanical properties [13]. Higher cooling rates lead to a decrease of ferrite grain size and formation of high strength, hardness, dislocation density, and fine phases because it suppresses the atomic diffusion [14]. In contrast for lower cooling rates where, slow cooling rates lead to transformation into soft, coarse, and less dislocated phases like polygonal ferrite [12,15].

The size and percentage distribution of ferrite and pearlite within the microstructure play an important role on the final mechanical properties. Each of the microstructure variables is highly influenced by the composition of the microalloyed steels, the forging parameters utilized, and the post-forging cooling rate. Variation in the cumulative amount of deformation, working temperatures and post cooling rates can engender a variety of microstructure [6]. The present work is aimed to study the effect of cooling rate after controlled hot forging on the mechanical properties of MC and MC–MA steels. This paper also envisages to find out the influence of vanadium concentrations on the microstructures and mechanical properties of MC–MA steel forged and then cooled at different cooling rate.

2. Materials and experimental procedure

The material used in this study was the commercial grade MC steel (AISI 1040) and MC–MA steel (38MnVS6). The chemical composition of these steels is listed in Table 1. The steels were supplied in the form of 50 mm diameter round bars and 1000 mm length billets. Steels were cut 200 mm length and 16 specimens were obtained for AISI 1040 and 38MnVS6 steels. The test specimens except those in the as-received conditions were solutionized at 1250 °C for 30 min in a induction furnace. Temperature before and after forging process was measured by using a infrared laser temperature measuring instrument. The experiments were performed with a 3.5 tonnes mechanical press. Close die forging was carried out to diameter reductions of 24% strain induced (calculated from the initial diameter 50 mm) in temperature range of 1250–950 °C. Then forged steel samples were cooled either in sand, air or oil. Room temperature tensile strength was measured according to the TS EN ISO 6892-1 [16] standard on a Schimadzu tensile-testing machine at a crosshead speed of 2 mm/min. Tensile test specimens were manufactured in accordance with the standard of TS EN ISO 6892-1 [16] as shown in Fig. 1. 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 10 hardness measurements was made on each specimen to obtain satisfactory statistical reliability.

Table 1
Chemical composition of the investigated steels (wt.%).

Steels	C	Si	Mn	P	S	V
AISI 1040 (MC)	0.41	0.17	0.68	0.001	0.010	–
38MnVS6 (MC–MA)	0.37	0.27	1.44	0.001	0.039	0.09

The examination of steel microstructures and fracture surfaces of the specimens were carried out using optic and scanning electron microscope (SEM), respectively. The specimens were polished according to standard metallographic methods for optical microscopy observations. The optical examination of the samples was carried out using an Nikon ECLIPSE L150 type microscope capable of magnifications between 50× and 1000×. The ferrite grain size, volume fraction of ferrite, and pearlite were determined by using mean linear intercept (mli) and point counting methods on etched metallographic specimens at appropriate magnifications. Scanning electron microscopy (JEOL 840A JXA) was also used to examine tensile fracture of the specimens representing the various testing conditions.

3. Results and discussion

3.1. Microstructure

The variation in mechanical properties in MC and MC–MA steels can be explained in terms of microstructure obtained during different cooling rates. Fig. 2 shows the evaluation of the microstructure for both MC and MC–MA steels under various cooling conditions. Table 2 also shows volume fraction of ferrite and pearlite and mean linear intercept grain sizes of ferrite in as-received, sand, air and oil cooled samples. As can be seen, for both steel, proeutectoid ferrite appears as a thin, continuous network at prior austenite grains and volume fraction of ferrite is decreased with increasing cooling rate (see, Table 2). These effects are generally associated with the influence of cooling rate on the coalescence and growth rates of ferrites [17]. Also increasing the cooling rate after finish forging at 950 °C led to finer ferrite grain sizes. An increase in cooling rates lowers transformation temperature and ferrite–pearlite form at lower temperature resulting in finer ferrite and pearlite grains [18].

When slow cooling rates are employed (sand cooling) recrystallization and even grain growth are expected to take place before the γ to α transformation [17]. The proeutectoid ferrite nucleates on austenite grain boundaries and the room temperature microstructure consists of a coarse ferrite network plus pearlite (Fig. 2). The microstructure of air cooled specimens is mainly composed of finer ferrite and pearlite in both MC and MC–MA steels. Small quantity of widmanstaten ferrite was also observed in MC steels. Widmanstatten ferrite forms at faster cooling rates than polygonal ferrite and in temperature ranges just below those at which equiaxed ferrite forms [7]. Oil quenching leads to a

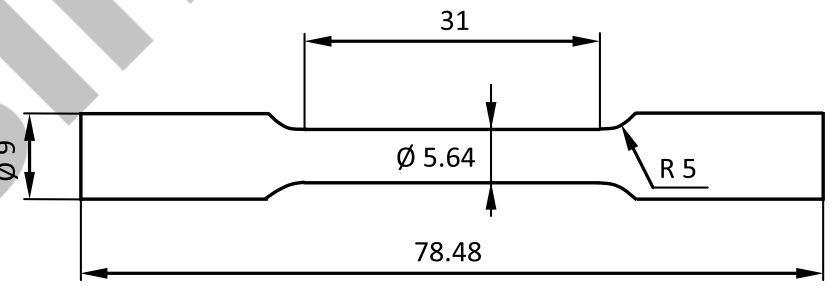

Fig. 1. Dimension of tensile test specimen.

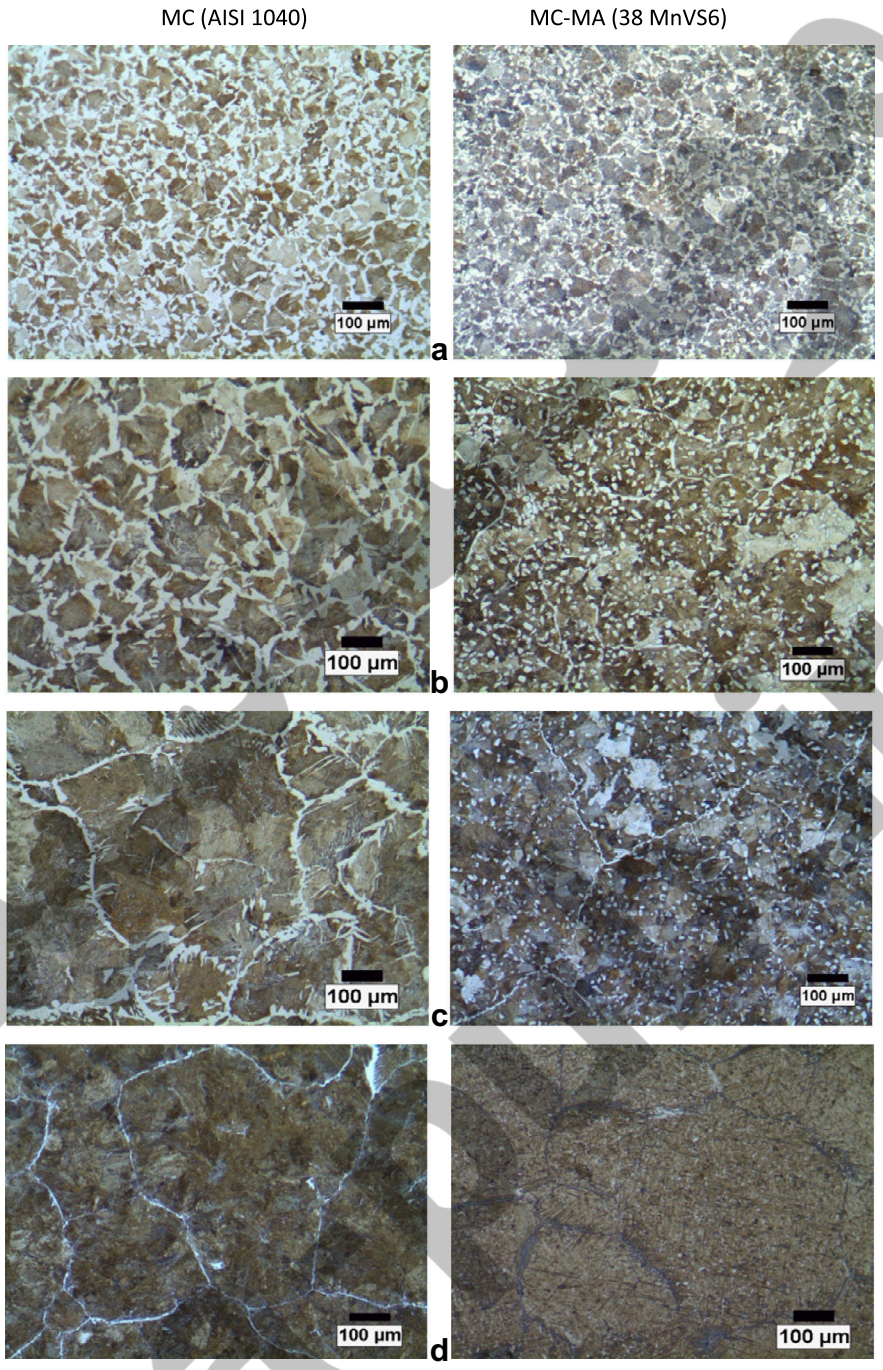

Fig. 2. Microstructures of MC and MC–MA steels under conditions of (a) as-received, (b) sand, (c) air and (d) oil cooled.

Table 2
Volume fraction of ferrite and pearlite and mean linear intercept grain sizes of as-received, sand, air and oil cooled samples.

Steels	Ferrite (%)	Pearlite (%)	Ferrite grain size (μm)
MC, as-rec.	35	65	13
MC, sand	35	65	15
MC, air	17	83	12
MC, oil	8	92	7
MC–MA, as-rec.	38	62	10
MC–MA, sand	27	73	11
MC–MA, air	15	85	8
MC–MA, oil	–	–	–

formation of relatively fine ferrite and pearlite in MC steel or martensite in MC–MA steels. 0.09% V in MC–MA steel may shift the TTT and CCT diagrams to longer times, permitting to obtain all martensite structure [18]. Martensite is not a desired phase due to its detrimental effect in toughness [19].

For the vanadium containing MC–MA steels was observed that proeutectoid ferrite appears as a discontinuous network and was more evenly distributed in the microstructure for as-received, sand and air cooled samples. It was found that increased proeutectoid ferrite volume fraction in MC–MA steels was accompanied by the presence of vanadium. V (CN) precipitates restricted the prior austenite grain size and enhanced the proeutectoid ferrite volume

because the grain boundaries represent sites for proeutectoid ferrite nucleation [20].

The presence of fine VCN particles in MC–MA steels during forging alters austenite grain growth and leads to fine ferrite–pearlite microstructure. It was observed that ferrite grain size in MC steel was approximately 12 μm and 15 μm for air and sand cooling respectively according to mean linear intercept method. However, the MC–MA steel had finer grain sizes which are 8 μm and 11 μm for air and sand cooling. This was probably caused by an increased concentration of vanadium since a level of 0.09% resulted in fine nucleation of VCN particles. The presence of VCN particles restricted the growth of austenite grain boundaries during forging at the temperature of 1250–950 °C and therefore resulted in the formation of a fine austenite grain size. The fine austenite grain sizes leads to fine ferrite grain sizes during cooling to room temperature. Because of vanadium precipitating particles in steels, recrystallization would be delayed and because these particles form at temperatures around 950 °C during cooling from austenite temperature, it can be deduced that recrystallization temperature is higher than the temperature at which participates start to form [21]. Due to the interaction of solute and precipitated vanadium, austenite recrystallization can be delayed to such an extent that it will practically be absent below a certain temperature. The vanadium precipitates formed would control the austenitic grain growth and the recrystallized austenitic grain size [22]. Thereby, these precipitates (vanadium carbonitrides and nitrides) reduce the ferrite–pearlite grain size obtained by decomposition of the austenite during cooling at rates close to air cooling [23,24].

From the solubility product data based on Narita [25], the solubility of VN is lower than VC. It is clear that VN is more stable than VC which are dissolved below 1000 °C. Thus, MC–MA steel contained V showed smaller grain size compared to the MC steel for all cooling conditions, because VN took part in pining process.

3.2. Mechanical properties

The mechanical properties of different thermo-mechanic conditions are shown in Fig. 3. It is clear from Fig. 3 that yield strength, tensile strength and hardness of MC and MC–MA steels increase with increasing cooling rate. The elongation tends to improve at lower cooling rate such as air cooling or sand cooling, however increasing the cooling rate has a negative effect on elongation. In oil quenched condition the steel attains a maximum UTS 663 MPa and 967 MPa for MC steel and MC–MA steel respectively. In MC steel, this is attributed to the formation of microstructure that is dominated by relatively fine ferrite and pearlite structure. However, in MC–MA steel condition this is arisen of hard martensite structure. Much of this strength in MC–MA steel has been derived from the carbon in solution in martensite [26]. The tensile strength value of 579 MPa and 743 MPa for MC steel and MC–MA steel respectively obtained in air cooling and dropped to 539 and 736 MPa in sand cooling. The decrease in tensile strength, yield strength or hardness along with increase in ductility of air or sand cooled samples of both MC and MC–MA steels are arisen from their microstructures that are dominated by coarse ferrite and pearlite structure. Furthermore, formation of a coarse precipitates that are less effective in impeding of dislocation motion is considered to be other parameter of decreasing the strength of MC–MA steel. The above results are in good agreement with earlier studies results [13–15].

By decreasing the cooling rate during eutectoid reaction, the distance that the atoms are able to diffuse is increased. Consequently, the lamellae produced during the reaction are coarser or more loosely spaced. By producing coarse ferrite and pearlite, the strength of the alloy is decreased [18]. The tensile strength is also quite sensitive to the pearlite content which explained by the fact that there is a linear relationship between work

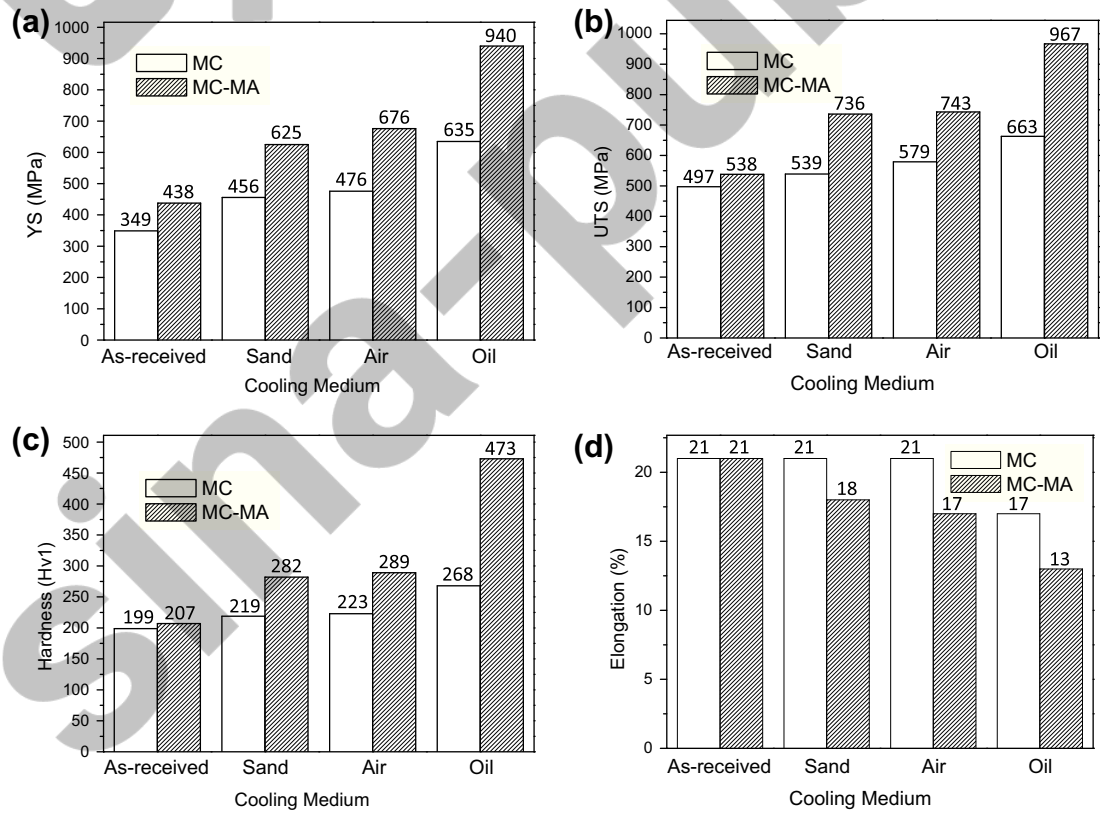

Fig. 3. A comparison of mechanical properties of different cooling mediums after forging: (a) yield strength, (b) tensile strength, (c) hardness and (d) elongation%.

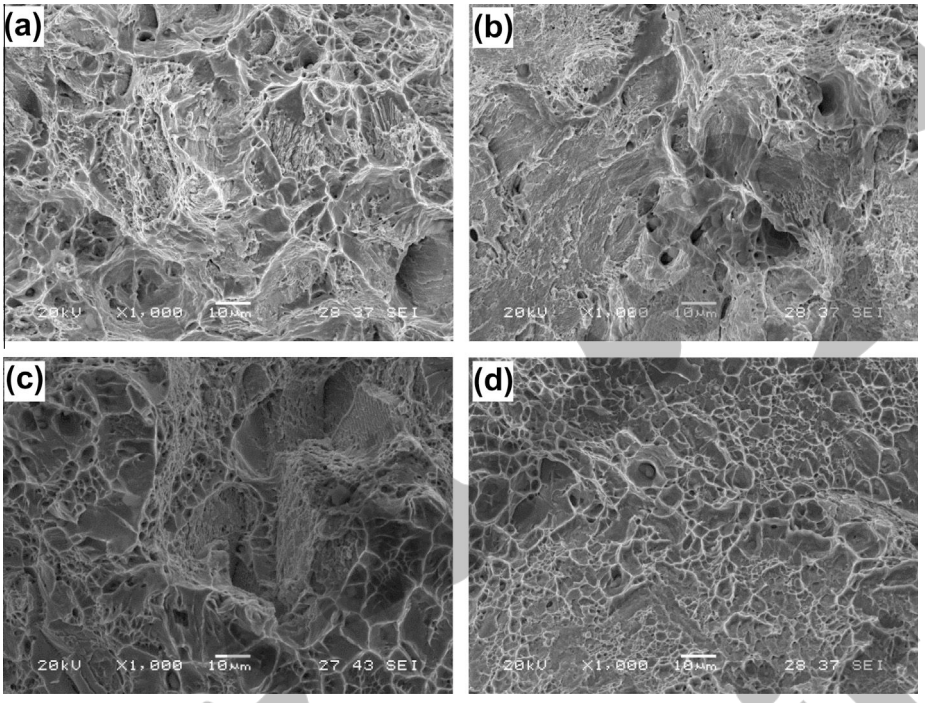

Fig. 4. Fracture surfaces of the MC steel forged and then cooled in different medium (a) as-received, (b) sand, (c) air and (d) oil.

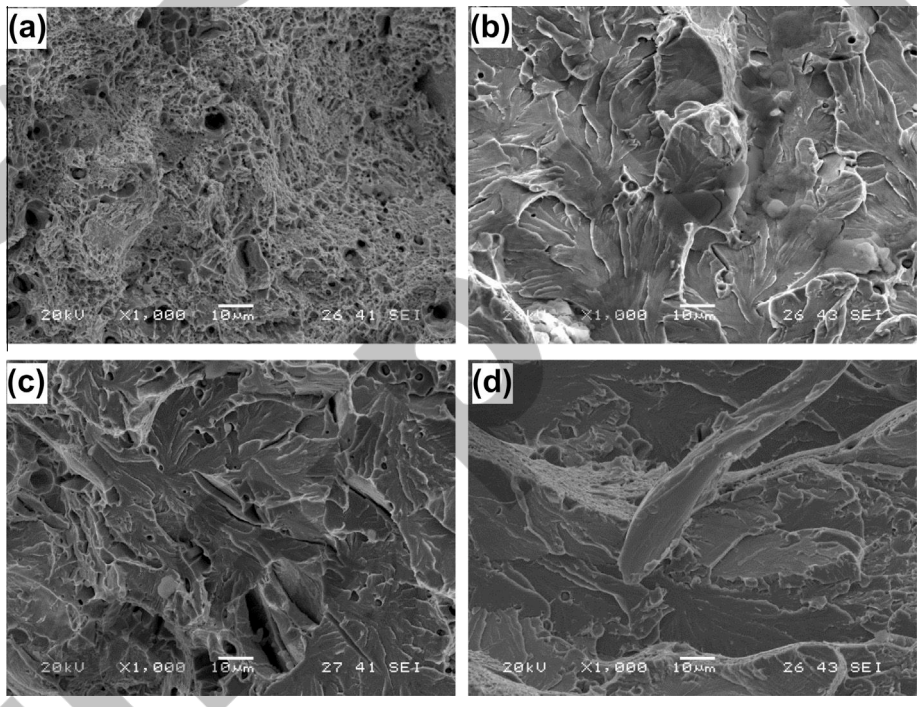

Fig. 5. Fracture surfaces of the MC–MA steel forged and then cooled in different medium (a) as-received, (b) sand, (c) air and (d) oil.

hardening and the pearlite content, which arises because pearlite work hardens much more rapidly than ferrite [23]. In a detailed study of the strength of eutectoid steels containing vanadium Ridley et al. [27] showed that the increase in strength produced by the addition of vanadium could be attributed to two features. Firstly, adding vanadium reduced the interlamellar spacing of the pearlite. This effect is undoubtedly due to a reduction in the temperature of transformation of austenite to pearlite. Secondly, at any given interlameller spacing of pearlite, the stress increased with increasing vanadium content and was accompanied by the precipitation of fine vanadium carbo-nitrides in the pearlitic ferrite. Bepari [28] also found very fine precipitate particles in continuously cooled low carbon vanadium steel and suggested that the faster cooling rates lower the transformation temperature and refine the precipitates resulting in clusters of fine particles of vanadium carbonitrides.

The tensile and hardness tests results of the investigated steels also indicated that the yield strength, tensile strength and hardness of the MC–MA steel are higher than MC steel for all cooling conditions (sand, air and oil cooling). The higher mechanical properties for MC–MA steel when compared MC steel, which has the same carbon concentration, is caused probably by increased vanadium content to about 0.09%. This is consistent with the results obtained by Ollilainen et al. [20] who showed an increase in vanadium content to 0.085% in medium carbon vanadium microalloyed steel resulted an increase in yield strength, tensile strength and hardness. It has been also shown that the added strengthening mechanism involved in medium carbon vanadium microalloyed steels is associated with vanadium carbo-nitride precipitation in both the proeutectoid ferrite and in the ferrite lamellae of the pearlite structure [29]. It can be noticed from Fig. 3 that micro additions of V has a significant strengthening effect. This can be attributed to its contribution in impeding of dislocation motion through formation of fine precipitates of carbides, nitrides or carbonitrides (precipitation strengthening) and/or by dissolving in the ferrite matrix (solid solution strengthening) [15,30].

The SEM micrographs of the tensile fracture surface of MC and MC–MA steels are shown in Figs. 4 and 5 respectively. As seen in Fig. 4, MC steel specimens cooled in sand, air or oil mediums after close die forging were characterized by the simultaneous presence of both a ductile morphology, with the typical dimples, and a brittle morphology with faceted features, typical of cleavage fracture. However, the tensile fracture surfaces of the MC–MA steel specimens cooled in sand, air or oil medium were mainly characterized by cleavage facets due to higher precipitation strengthening in sand and air cooled samples and the presence of martensite in oil quenched samples (see Fig. 5). The reduction in area also decreased which corresponds to embrittlement due to interaction between dislocation and precipitate particles. This morphology is in agreement with the results of the tensile tests in Fig. 3. Vanadium microalloyed medium carbon steels with ferrite–pearlite microstructures have been produced with the equivalent as-forged or as-rolled strength as the quenched and tempered steels, but their toughness has not usually been as good. In a similar way, the strength of pearlitic steels has been improved by V addition, but toughness is not improved in the same way [21]. In the case of as-forged and as-rolled microstructures, different approaches have been considered in order to improve their toughness, the most relevant being the refinement of the austenite grains (Ti microalloying) and the application of accelerated cooling.

4. Conclusions

This paper had the aim of investigating the effect of the close die forging and different cooling rates on mechanical properties of MC and MC–MA steels. The main conclusions from this study are as follows:

(1) Higher strength combined with adequate elongation to fracture can be achieved in MC and MC–MA steels by forging followed by air cooling. This strength and elongation to fracture obtained is due to finer grain sizes and the larger pearlite and/or precipitation contributions.
(2) MC–MA steels had higher strength, hardness and lower percentage elongation compared to MC steels for all cooling conditions due to an increase in vanadium content to about 0.09%. Vanadium addition raised strength and hardness by precipitation strengthening and by refining the ferrite and pearlite.
(3) Although the strength of the MC and MC–MA steels is high, a drastic fall in elongation to fracture values are obtained when the steels are cooled in oil. Oil quenching leads to a formation of relatively fine ferrite and pearlite in MC steel or martensite in MC–MA steels.
(4) Sand cooling from forging temperature results in a decrement of strength (yield and tensile strength) in MC and MC–MA steels. This is because of the lowest cooling rate resulted in coarse precipitates, ferrite and pearlite grain sizes.

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