The effect of Vanadium Micro-alloying and Hot Deformation Control on the Mechanical Properties of Structural Steel

Eman El-Shenawy, Taher El-Bitar, Almosilhy Mohammed

Abstract— Structural steels are considered as important engineering materials, where, they are introduced in machinery construction especially in connecting rods processed by hot forging. These parts require high strength in combination with good toughness. Better properties could be achieved by making combinations of the different strengthening mechanisms. Increasing the carbon content of the steel is the common way to raise strength by increasing the pearlite percentage in the microstructure, however, both ductility and weldability are highly deteriorated. Micro-alloying with Vanadium is a convenient solution, where vanadium has proven to be a popular choice as a microlloying for structural steels. In addition, hot deformation control makes complete benefit from V-microalloying. The present work is dealing with investigation of two steel alloys. The first alloy depends mainly on alloying with carbon, while the second one contains less carbon but strengthened with vanadium micro-allying. The two alloys were subjected to extensive hot deformation by forging under the same conditions of heating and finishing. Microstructure, and mechanical testing as well as fractography after mechanical properties were investigated. It is concluded that extensive hot deformation by forging enhanced ductility through grain refinement of both steel alloys where the hard constituents were homogeneously distributed. In the V-micro-alloying steel, grain refinement enriched the V(C,N) precipitates distribution in the matrix. Both alloys had excellent tensile properties, while v-micro-alloyed alloy exhibited better impact properties

Index Terms— Structural steels, vanadium micro-allying, hot deformation control, V(C,N) precipitates,

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1 Introduction

Efforts were made in the last century to reduce post hot forming heat treatment costs through micro-alloying additions. High-strength low-alloy (HSLA) steels, or microalloyed steels, are designed to meet specific mechanical properties rather than a chemical composition [1][2]. Improved toughness and high strength could be fulfilled only by refining the microstructure and reducing the amount of second phases, such as inclusions and pearlite phase.

Several hot forming and cooling regimes have been developed to achieve this goal, guaranteeing steel to maintain its position as the most relevant metallic material [3].

Microalloyed-medium-carbon steels that form large volume fractions of pearlite are typically used for forgings. Higher carbon steels contain high pearlite volume fraction and provide higher strengths. However pearlite is sensitive to cleavage fracture and consequently the higher carbon steels have lower toughness. Lowering carbon content and reducing pearlite colonies size by deformation affect positively the toughness properties [4][5].

High strength and adequate ductility properties can be achieved in steel by controlling phases in the microstructure [6].

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Multiphase microstructures consisting of polygonal ferrite, pearlite, bainite and martensite can be produced in a wide variety of HSLA low carbon steels as a result of appropriate combinations of chemical composition, thermomechanical processing and accelerated cooling conditions [7][8]. Hardness increases with the increase of the cooling rate primarily due to microstructural change from ferrite-pearlite duplex structure to martensite and/or bainite [9]. The optimum cooling rate exhibiting good combination of strength and toughness for medium carbon microalloyed steels would be 0.5-2°C/sec (air cooling) so as to avoid both bainite formation by fast cooling and overaging by slow cooling.

Hardening of ferrite phase in V-microalloyed steel is mainly due to precipitation of fine V(C,N) particles. High solubility of the V(C,N) precipitates permits high alloy levels in the steel. Precipitation occurs primarily during or after transformation to ferrite, thereby not contributing to roll forces during finish rolling. The carbon content of pearlite in microalloyed steel is higher than that of plain carbon steel because of larger ferrite volume fraction. The carbonitride particles form during cooling on the interfaces between austenite and ferrite, and as the ferrite grows, rows of precipitate particles are imbedded in the ferrite [4][10].

Vanadium forms almost no austenite precipitates and is plentifully available for precipitation hardening during or after the γ/α transformation [11]. It was reported that YS and UTS linearly increases with increasing V content up to 0.15% due to precipitation of fine carbo-nitride V(C,N) during cooling after hot forging [12][13]. The carbo-nitride precipitates affect positively on the yield strength, where microalloying with 0.08% V

International Journal of Scientific & Engineering Research, Volume 8, Issue 12, december-2017
ISSN 2229-5518

increases the yield strength of the steel by 180 MPa. The homogenous distribution of pearlite phase by hot deformation in V- bearing alloy damps the brittle negative effect of V[C, N]. However, V-microalloying has no pronounced effect on lowering the impact transition temperature[1]. Duckworth et al. [10], proposed that improving weldability and toughness of medium carbon steel is associated with lowering C-content, V/Nb-microalloying and low finishing temperature deformation.

In the present investigation, two steel alloys were examined. The first steel alloy contains 0.42% C, while the second one is V-microalloyed steel with 0.22% C. Attention was paid to elucidate the effects of hot forming and microalloying on the microstructure and mechanical properties.

2 Materials and Experimental Work

The chemical composition of the present steels under investigation is listed in table 1.

TABLE 1
CHEMICAL COMPOSITION OF STEELS UNDER INVESTIGATION

Element,% / Grade	C	Si	Mn	P	S	Al	V
Alloy 1	0.42	0.21	1.43	0.035	0.014	0.022	0.017
Alloy 2	0.22	0.34	1.40	0.016	0.019	0.016	0.087

The steel grades were continuously cast as 130 x 130 mm square billets. The steel billets were then sliced to 42 x 64 x 200 mm slices.

The two steels were austenitized at 1200°C and hold for 60min. The slices were then open die hot forged to bars with 15.16 mm diameter for steel 1 and 18.45 mm diameter for steel 2. Forging has been continued down to 800°C, the forged bars were then air cooled as shown in figure 1.

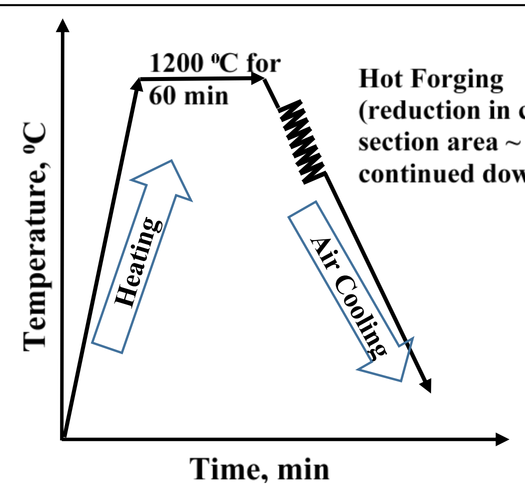

Fig. 1. The hot forging process

Tensile tests were conducted with crosshead speed 10 mm/min and Charpy V-notch impact tests were carried out at the room temperature on specimens, which were taken from the longitudinal direction of the forged bars. Hardness was measured on a Vickers scale. Microstructures were examined through the optical microscopy. After mechanical testing, the surface of the fractured specimens was investigated by Scanning Electron Microscope (SEM).

3 Results and Discussions

V(C,N) precipitation is one of the major strengthening mechanisms responsible for improvement of strength in the medium carbon pearlitic steels and is widely applied in the development of high-strength low-alloy (HSLA) steels.

The chemical composition stated in Table 1 clearly show that the 1st steel alloy is a plain-carbon steel with 0.4% C. On the other hand, the 2nd steel alloy contains less carbon (0.22%) in combination with vanadium microalloying.

Figure 2 represents the microstructure of both steel alloys after forging. It is obvious that both micrographs contain ferrite grains with pearlite colonies. The pearlit constituent of alloy 1 occupies large continuous portion of the structure, which may deteriorate the toughness [7]. On the other hand, pearlite occupies less area in the microstructure of alloy 2. Pearlite appears as isolated colonies. This may be attributed to both lower carbon and due to precipitation of V(C,N) on cooling at the interfaces between austenite and ferrite phases and working as sites for ferrite grains growing, isolating pearlite, which is formed later [8]. High amount of deformation, > 90%, introduces further sites for ferrite nucleation through austenite conditioning [14].

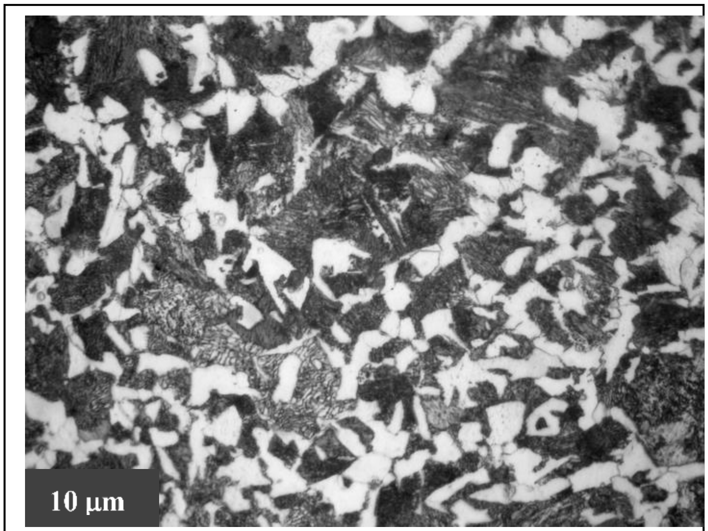

Fig. 2 (a). Alloy 1

International Journal of Scientific & Engineering Research, Volume 8, Issue 12, december-2017
ISSN 2229-5518

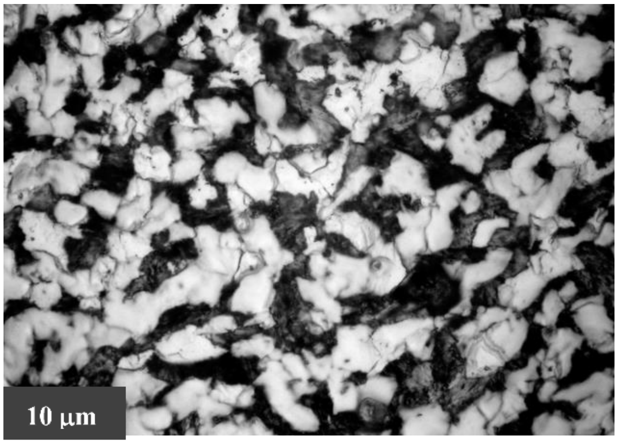

Fig. 2 (b). Alloy 2
The Microstructure of both steel alloys after forging, [×1000].

The mechanical properties are considered as a mirror of the strengthening mechanism introduced to the alloy. Figure 3 presents the tensile properties of both alloys. The yield strength of alloy 2 is higher than that of alloy1 inspite of the carbon content of alloy 2 is lower than that of alloy 1, Elongation nearly the same. This may be attributed to the effect of both v-micro-alloying and hot deformation, where extensive hot deformation conditioned austenite [14], During transformation of conditioned austenite to ferrite V carbo-nitrides are precipitated [11][12], leading to creation of finer ferrite grains and isolated colonies of pearlite as it is manifested by both microstructures in Figure 2 [14].

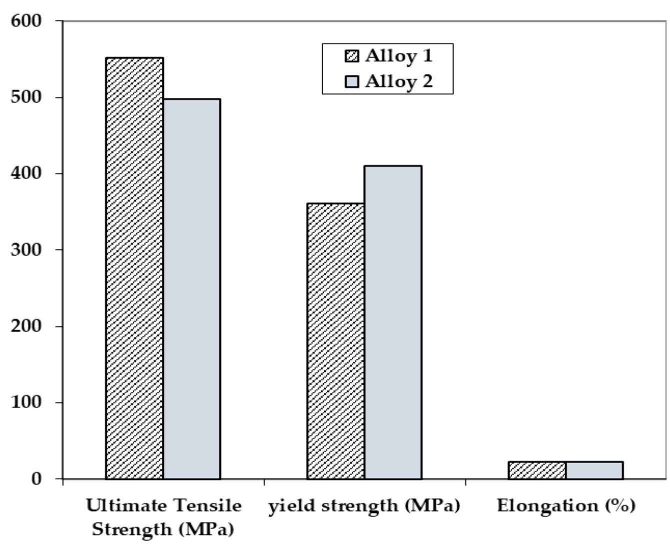

Fig. 3. Tensile properties of both alloys

Figure 4 represents SEM fracture surface of tensile specimens of both steel alloys. It is clear that the fractographs of both alloys are classified as ductile fracture where full dimples are presented.

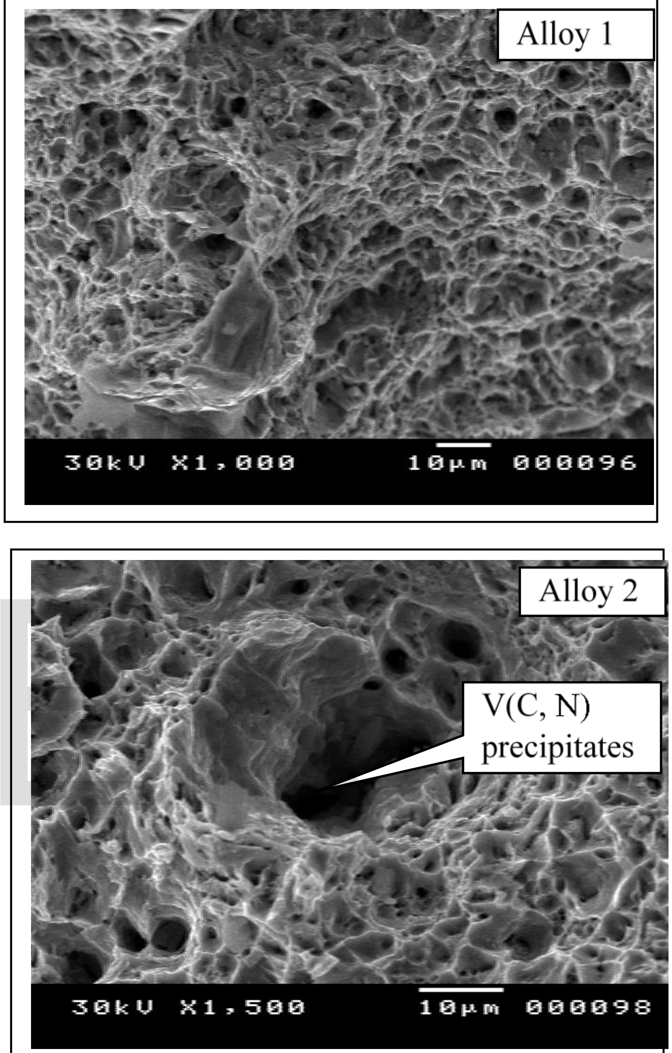

Fig. 4. SEM fracture surface of tensile specimens of both steel alloys.

The fracture surface of V-microalloyed steel (Alloy 2) contains troughs where the V(C,N) precipitates are found.

Lowering the C-content and V-microalloying to the steel alloy 2 are clearly reflected on comparing the impact resistance of both alloys in Figure 5. Steel 1 which contains 0.42% C has toughness of 2.75 Kgf.m, where steel 2 scores toughness of 15 Kgf.m. The continuous area occupied by the pearlite hard phase in steel 1 affects negatively on the impact toughness as well as on the ductility, [4][15], whereas V(C, N) precipitates and the isolated colonies little portion of pearlite in steel 2 affects positively on toughness.

International Journal of Scientific & Engineering Research, Volume 8, Issue 12, december-2017
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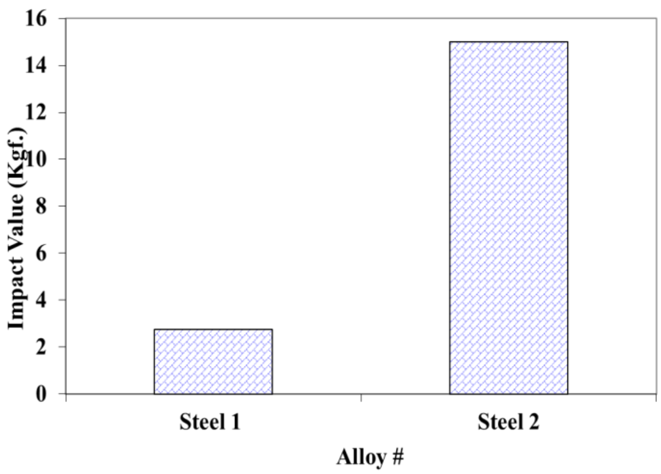

Fig. 5. Impact energy of both steel alloys

5 Conclusion

1. Pearlit constituent of C-steel alloy occupies large continuous portion of the microstructure, however it occupies less area and appears as isolated colonies in the V-microalloying steel.
2. V(C, N) precipitation in V-micro-alloying steel and conditioning of austenite during hot deformation improve yield strength and do not affect negatively elongation.
3. V- precipitates lead to the formation of troughs on the full dimpled fracture surface of V-microalloyed steel
4. C-steel alloy has lower impact toughness than that of V-microalloying steel.

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