Mechanical Properties Improvement of Low Carbon Steel by Combined Heat Treatments

J. Abou-Jahjah and **J. Dobránszky.***

ABSTRACT:

The improvement of the Mechanical properties of the low Carbon steel and increasing its strength, was the goal of some heat treatment technologies developed in the last twenty years. One of these technologies is the Rapid Heat Treatment (RHT), by which the strength of steel increases with the crystalline grain size decrease obtained from the rapidity of austenitizing, and more strength increase may be obtained, if the action of austenitizing is followed by rapid cooling or quenching, but in this case, ductility will decrease simultaneously by increasing the cooling rate.

Another mechanical properties improving heat treatment, is the Intercritical Heat Treatment (IHT), by which the ferrite-pearlite structure of low Carbon steel transforms to Dual-Phase structure of ferrite and martensite resulting increase in strength, while a great deal of its ductility is restored.

Authors in this paper report about their experiments carried out on a low Carbon-steel, trying to get the advantages of the two above mentioned technologies, by subjecting the formerly rapid heat treated steel, to intercritical heat treatment,. Applying this treatment on the steel in different temperatures inside the intercritical zone, remarkable results were obtained and reported..

* **Jamil Abou-Jahjah**, Dr. Eng. Prof. University of Damascus. Faculty of Mechanical and Electrical Engineering, Damascus P.O.B. 86, Syria, Fax: (**963) 11-5423296 ; and **János Dobránszky**, Dr. Eng. Member of the research group for metals technology of the Hungarian Academy of Sciences, Technical University of Budapest, Goldman Gy. tér 3,Hungary, Fax: (**36) 1-4633250.

INTRODUCTION:

The mechanical properties of any structural metallic material - with certain chemical composition - are functions of its micro- structure. So the aim of any heat treatment technology is the improvement, or control of the mechanical properties by controlling the microstructure to suit the requirements restricted on a certain piece, even for use, or for subjecting to a forming or machining technology

The Rapid Heat Treatment (RHT) is one of the newly developed technologies to improve the mechanical properties of low Carbon steels, by annealing it at a temperature above A_{C3} to be transformed to austenite in a very short time (0,001 - 0,5 sec.) which can be achieved by using the Joule heat of the steel itself (Ref. 1), and then cooling it by different rates. The mechanical properties improvement especially strength is (in compliance with Hall-Petch equation) a function of the grain size of the transient phase (austenite), which depends on the heating and transforming rate (Ref. 1,3), and a function of the quality of the final microstructure, which depends on the cooling rate.

RHT experiments carried out using two types of low Carbon steels, show that, tensile strength could be increased up to 200 % of its original value, with a moderate decrease of its elongation (Ref. 1) .

Another effective heat treatment for improving the mechanical properties of low carbon steels is the Intercritical Heat Treatment (IHT), in which the original ferrite-pearlite structure, transforms to dual-phase structure of ferrite and martensite. In this treatment, the steel is annealed at a temperature within the intercritical zone (between A_1 and A_3) at where the pearlite and a part of ferrite (depending on temperature) transform to austenite¸ and then quenched or cooled in a high cooling rate to transform the austenite to martensite. The higher the annealing temperature selected in this zone, the more austenite forms and transforms to martensite, but the less Carbon content in this Martensite (Ref. 4,5,6).

Other version of IHT is the Reversed Intercritical Heat Treatment (RIHT) , by which martensite in dual phase structure can be controlled to form a network or massive matrix around the ferrite, otherwise the ferrite surrounds the martensite while the later is less then 50 %. , and more mechanical properties improvement may be gained by this technique (Ref. 2).

The essential point of the Reversed Intercritical Heat Treatment is that, the steel should be treated by two steps. The first step is the annealing of the steel at a temperature above Ac_3 and quenching it to have martensite structure (in low carbon steel cubic martensite is forming), the second step is the intercritical annealing and quenching again. At annealing at an intercritical temperature the austenite starts to appear and grow on the crystalline boundaries forming a network, which transforms to martensite at quenching (Ref. 2).

We suppose that, if a rapid heat treated steel is subjected to intercritical heat treatment, more mechanical properties improvement may be gained. So the goal of this work was the clarification of this supposition, and finding the intercritical annealing temperature, or temperature interval from which quenching results better mechanical properties.

EXPERIMENTS:

The experimental material was a rapid heat treated low carbon steel wire, with a diameter of 5,5 mm.. The chemical composition of the steel is shown in table 1.

Table 1.: The chemical composition of the steel.

C%	Si%	Mn%	S%	P%
0,12	0,14	0,56	0,01	0,020

The microstructure of the steel as rapid heat-treated is shown in (figure 1), and its mechanical properties in its original state, and after rapid heat treating is shown in table 2.

Table 2.: The mechanical properties of the steel before and after (RHT).

Mech.Prop.	R_m (MPa)	R_e (MPa)	A_5 %
Original	370	235	25
After RHT	770	600	8

Tension specimens were prepared, from the formerly rapid heat-treated steel, grouped into sets and numbered. Every set of specimens was heated and hold for 15 minutes at one of the 11 different temperatures, 8 of them were between A_1 and A_3, one temperature was about the calculated Ac_3 and the other 2 were above it. The calculated Ac_3. considering the chemical composition of the steel (Ref. 7) is about : 850°C.

By finishing the heat treating, all specimens were subjected to tension test on an Instron universal testing machine, selecting a constant loading speed of 2 mm/min. The tension test results are included in table 3 and diagram (figure 2).

Table 3 : The mechanical properties of the steel after IHT.

Spec. set No.	annealing temperature [°C]	Ultimate tensile strength: R_m [MPa]	Yield strength: $R_{P0,2}$ [MPa]	Total elongation: A_5 %
1	735	695	475	25
2	750	716	495	24
3	765	760	530	20
4	780	785	550	19
5	795	850	610	20
6	810	860	640	18
7	825	910	730	17
8	840	1170	1020	14
9	850	1050	920	15
10	865	1080	985	11
11	880	1068	975	12

Microscopic test specimens from one broken tension specimen of every set, ware cut, sectioned (longitudinal and cross sectional), prepared and examined by light microscope. (Figure 3), shows samples of microstructures of intercritically heat-treated specimens, annealed at different temperatures. (SEM) micrographs were prepared about fracture surfaces of some specimens, one of these belongs to specimen annealed at $810^{o}C$ is shown in figure 4. It illustrates the characteristics of Dual-Phase fracture, where equiaxial dimples characterize the ferrite fracture (fig. 4a) and quasi-cleavage are observed where martensite are existing (fig. 4b).

RESULTS AND CONCLUSIONS:

From results obtained from tension tests (table 3 and fig. 2) the followings could be concluded and discussed:

Taking in consideration that the tensile strength of the used steel in its original state is about 370 MPa, and after RHT it can reach 800 MPa, considerable increase in its tensile strength could be achieved by subjecting it to IHT, with the proper selection of the annealing temperature,(1170 MPa after quenching from $840^{0}C$). Farther more, as it is obvious from (figure 2), a wide range of combination between strength and elongation could be controlled.

The mechanical properties achieved by IHT are functions of the annealing temperature. So the tensile strength increases with rising of the annealing temperature (because the martensite content in the structure is increasing), with slight decrease of elongation.. The tensile strength in our case has reached its maximum value where the annealing temperature was $840^{0}C$, and by using higher temperatures, although martensite content in the structure was still increasing the tensile strength started slightly to decrease, which seems to be in a contradiction with the impression of martensite increase. But however it is evident that when martensite increases in the Dual-Phase structure in the same steel, the carbon content of this martensite will decrease by sliding up on the GS line in the phase diagram, and its ductility and formability also increases. The changes of martensite volume fraction and its carbon content with annealing temperature as calculated with reference to the phase diagram is shown in (figure 5), and the developing of plastic deformation of martensite with the annealing temperature can be observed in (figure 6).

When the carbon content in martensite decreases to about 0,25%, then cubic martensite will start to exist instead of tetragonal martensite. So the decrease of tensile strength may be due to the increasing existence of the cubic martensite, and if it is so, that means the annealing temperature which results the max. tensile strength (optimum temperature) is the same for all low carbon steels in which the carbon content does not exceed the 0,25 % and when only carbon is the dominant component. But if other components are existing in the steel such as Si, Ni, V, Mo. ... etc., then this temperature will vary in the same way A_{c3} varies. Since elements contained in steel effect the optimum annealing temperature, from which quenching results maximum tensile strength, in the same way they effect the Ac_3. The determination of this temperature can be roughly done by calculation from the composition of the steel, considering the carbon content 0,25 %, whatever the real content is. But better result needs to combine the calculation with experiments.

It is most likely be that the decrease of strength started from the so-called optimum temperature is attributed to grain size growth of the structure. The annealing time in our experiments was the same (15 min.) at all temperatures, and at higher temperatures this period was more long than that needed to homogenize the existing elements in the structure and grain size was simultaneously increased by rising the temperature. So better results and no jutting out optimum temperature could be obtained if the annealing time is simultaneously reduced by rising the annealing temperature, taking in consideration the quality and quantity of existing alloying elements and diffusion conditions at different temperatures.

The prediction of mechanical properties of Dual-Phase steel based on mixture-role calculation (Ref 8) should take in consideration not only the volume fraction of martensite but also the variation of its properties due to variation of its carbon content by varying the annealing temperature.

The final structure obtained from RHT with continuous cooling may be (in addition to the retained austenite) ferrite-pearlite, ferrite-pearlite-bainite-martensite, ferrite-bainite-martensite, or martensite according to the cooling rate executed, but none of the phases which compose any of those structures are homogeneous, especially the last two structures, because the short transformation period to austenite during RHT and short holding time in the austenite zone, do not give diffusion the opportunity to homogenize the carbon in the austenite, and heterogeneous austenite will transform to heterogeneous phases, especially when high cooling rates are executed. Therefore it is advisable to follow RHT by IHT even if sufficient or required strength was obtained from RHT because homogeneity and more ductility can be gained.

The Rapid Heat Treated steel used in this work was cooled with somewhat lower cooling rate then its critical cooling rate, so its structure was containing ferrite, pearlite, bainite and martensite, But when the cooling rate exceeds the critical one, and martensitic structure is obtained, then the following intercritical heat treatment could be considered as Reversed Intercritical Heat Treatment (RIHT), in this case transformation to austenite at intercritical annealing needs shorter time than usually at IHT and great deal of grain growth could be avoided with more controllability of structure and properties.

ACKNOWLEDGMENTS:

The permission of Professor J. Ginsztler, head of department of Mechanical Technology and Material Science, and Professor I. Artinger, deputy head of department, to use the facilities of their department. Their help and support. The help of all Colleagues and workers of the department. Are gratefully acknowledged.

The useful discussions have been had with Professor J. Prohászka, and his helpful advises worth to be specially acknowledged and thanked.

REFERENCES:

1. J. Prohászka, J. Dobránszky, Quality Improvement of Low Carbon Reinforcing Steel by Rapid Heat Treatment, J. Heat Treating , Vol. 9, No. 1, 1991, p 63-67., Springer Verlag, New York Inc.
2. J. Abou-Jahjah, The effects of Heating Temperature and Distribution of Martesite on the Mechanical Properties of a Dual-Phase Steel (Arabic and English), Proc. of the 2nd Jordanian International Conf. on Mech. Eng. Amman, 1997, Vol. 2, p. 853-865, Pub. Org. Comm. Dr. M. Hammad Chairman, Ed. Jor. University, 1997.
3. J. Bénard, A. Michel, J. Philibert and J. Talbot, Métallurgie Générale, 2e- éd. Masson, Paris, 1991,p 179.
4. G. Krauss, Principles of Heat Treatment of Steel, p.240-246, Ed. M. A. Grossmann and E.C. Bain, Pub. ASM, Ohio, 1980.
5. G. R. Speich, Physical Metallurgy of Dual-Phase Steels, p. 4-10 in Fundamentals of Dual-Phase Steels, Conf. Proc. The Metal. Soc. of AIME 1981, Ed. R.A. Kot and B.L. Bramfitt, Warrendale, Pa. 1981.
6. Pierre Messien, Jean-Claude Herman, Tony Gréday, Phase Transformation and microstructures of intercritically annealed Dual-Phase Steels, p. 161 in Fundamentals of Dual-Phase Steels, Conf. Proc. The Metal. Soc. of AIME 1981, Ed. R.A. Kot B.L. Bramfitt ,. WarreNdale, Pa. 1981.
7. B. L. Bramfitt, Anil K. Hingwe Annealing of steels, ASM Handbook, Vol. 4, Heat treating, USA 1991, p. 42-55
8. G. R. Speich, Tempering of Ferrite-Martensite Steels, p. 279-303 in Fundamentals of Dual-Phase Steels, Conf. Proc. The Metal. Soc. of AIME 1981, Ed. R.A. Kot and B.L. Bramfitt, Warrendale, Pa. 1981.

FIGURE CAPTIONS:

Fig. 1 The microstructure of the rapid heat treated steel used in experiments,(500x).

Fig. 2 Variation of mechanical properties of the intercritically heat treated steel with annealing temperature

Fig. 3 Variation of Dual-Phase structure as quenched from different annealing temperatures, a.) quenched from 750^{o}C, b.) quenched from 780^{o}C, c.) quenched from 810^{o}C, d.) quenched from 840^{o}C and e.) quenched from 865^{o}C, (500x).

Fig. 4 Fracture surface (SEM) micrograph of tension specimen annealed at 810^{o}C.

Fig. 5 Variation of martensite volume fraction and its carbon content with annealing temperature.

Fig. 6 Development of plastic deformation of martensite with rising the annealing temperature, a.) quenched from 750^{o}C, b.) quenched from 780^{o}C and c.) quenched from 810^{o}C, (500x).

Fig. 1 The microstructure of the rapid heat treated steel used in experiments.

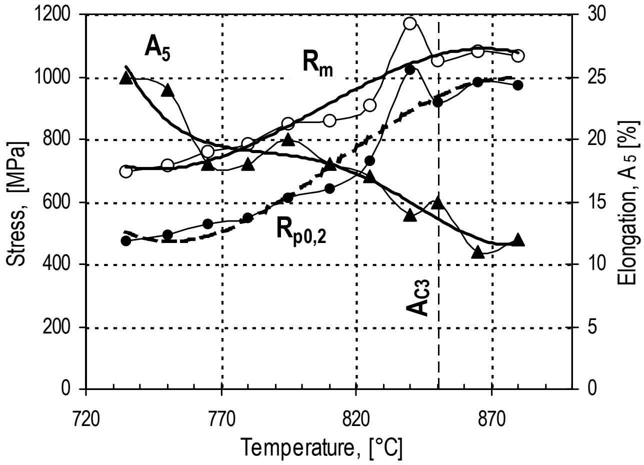

Fig. 2 Variation of mechanical properties of the intercritically heat treated steel with annealing temperature.

Fig. 3 Variation of Dual-Phase structure as quenched from different annealing temperatures, a.) quenched from 750^{o}C, b.) quenched from 780^{o}C, c.) quenched from 810^{o}C, d.) quenched from 840^{o}C and e.) quenched from 865^{o}C.

Fig. 4 Fracture surface (SEM) micrograph of tension specimen annealed at 810^{o}C.

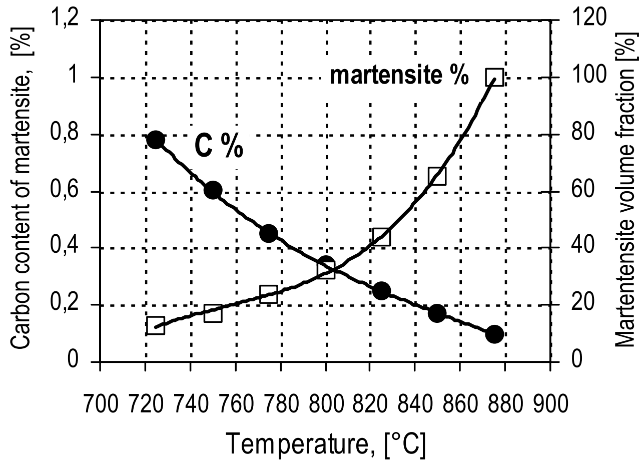

Fig. 5 Variation of martensite volume fraction and its carbon content with the annealing temperature.

Fig. 6 Development of plastic deformation of martensite with rising the annealing temperature,

a.) quenched from 750^{o}C,

b.) quenched from 780^{o}C and

c.) quenched from 810^{o}C