EFFECT OF Q-P PROCESS PARAMETERS ON THE MICROSTRUCTURE AND MECHANICAL PROPERTIES OF SECURE 400 STEEL

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SECURE 400 steel is used for basic ballistic protection of armoured vehicle chassis against the pressure energy of exploding mines, IEDs and grenades. It is a low-alloy high-strength steel with a manufacturer's declared hardness of 380 to 430 HB, which is characterized by a good combination of high strength and toughness. As standard, this steel is processed by quenching followed by tempering, but new possibilities for improving its mechanical properties are constantly being sought. A modern heat treatment process, the so-called Q-P process, leads to the formation of a multiphase structure, which positively influences the mechanical properties. Therefore, this paper focuses on describing the influence of Q-P process parameters on the development of the microstructure and mechanical properties. During the experimental program, it was found that the Q-P process increased the ultimate tensile strength by up to 300 MPa and increased the hardness by up to 68 HV10 compared to the post-delivery condition where tensile strength and hardness values of 1354 MPa and 438 HV10, corresponding to 414 HB, were measured. Redistribution of the carbon from the supersaturated martensite stabilised the austenite and a finer grained microstructure was achieved.

KEYWORDS

SECURE 400 steel, heat treatment, Q-P process, mechanical properties, microstructure

INTRODUCTION

SECURE 400 ballistic steel plates are mainly used for basic ballistic protection of armoured vehicle chassis. These low-alloy, high-strength structural steel plates are characterised by higher hardness and strength while maintaining toughness, which has positive effects against the compressive energy of exploding mines, IEDs and grenades, where the plate is required to absorb the blast without rupturing. These properties are achieved by the presence of alloying elements that lead to the precipitation of carbides during thermomechanical and heat treatment [PELLEGRINI 2020,]. The ballistic steel SECURE 400 is also known by the designation according to EN - 30CrMoNb5-2 [YUMPU 2023]. In general, SECURE 400 steel acquires its mechanical properties after a prescribed heat treatment consisting of quenching and tempering (the Q-T process). The heat treatment depends on the chemical composition and thickness of the product. In order to avoid a reduction in hardness during use, SECURE 400 steel must not be heated to temperatures higher than 400 °C [YUMPU 2023]. In addition to the development of new alloying concepts, the ever higher demands on mechanical properties have led to the development of new heat treatment processes. One of these is the Q-P process. The Q-P process consists of quenching from the austenitisation temperature to a temperature between the start of martensite formation Ms and the end of martensite formation Mf. This is followed by heating to a temperature just below or around the Ms temperature, and then isothermal holding. The isothermal holding temperature allows the redistribution of the carbon that diffuses from the supersaturated martensite formed during quenching, in which the carbon has a very low solid state solubility, into the remaining austenite. The higher carbon content ensures that the austenite is stabilised against martensitic transformation during the final cooling to room temperature. When using the Q-P process in heat treatment, the formation of bainite and pearlite is undesirable [BUBLIKOVA 2018]. The experimental programme was focused on the description of the change of the microstructure and mechanical properties of SECURE 400 steel sheets after heat treatment by the Q-P process. The increase in strength while maintaining sufficient toughness should have a positive effect when using ballistic sheets in chassis construction by reducing the required thickness of the ballistic sheets, resulting in a reduction in vehicle weight while maintaining ballistic resistance. If the thickness of the ballistic plates was maintained, the ballistic resistance of the vehicle would be increased.

EXPERIMENTAL PROGRAMME

SECURE 400 steel (Table 1) [KAISER 2011] was used for the experimental programme and was supplied as 3.3 mm thick plate.

C	Si	Mn	P	S	Cr	Ni	Mo	Al
0.32	0.4	1.0	0.015	0.005	1.5	0.7	0.5	0.11

Table 1. Chemical composition of SECURE 400 steel sheet in wt.% [*KAISER 2011*]

The most important phase transformation temperatures for the correct design of the experimental programme were calculated in JMatPro (Table 2) and the anisothermal decay CCT diagram of austenite (Figure 1).

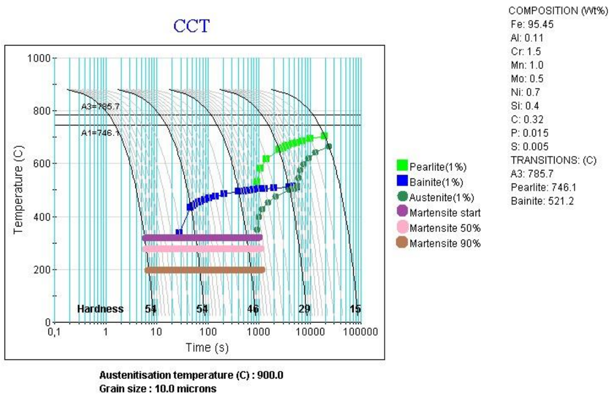

Figure 1. CCT phase diagram of SECURE 400 steel

The CCT diagram plots the start and end of austenite transformation and the resulting structure for different cooling rates. The slow cooling of the eutectoid steel produces a pearlitic structure. As the cooling rate increases, the beginning and end of the transformation shifts to lower temperatures and shorter times. When a certain cooling rate is reached, a structure consisting of pearlite and bainite is formed. At higher cooling rates a martensitic structure is formed. The higher the cooling rate, the steeper the curve that represents it [PTACEK 2002].

A_3 [°C]	M_s [°C]	M_{50} [°C]	M_f [°C]
786	316	280	197

Table 2. Temperature of austenitisation, martensite start, martensite 50% and martensite finish

For the Q-P process, 20x30 mm samples were cut from the supplied sheet metal. Following the calculated values in Table 2, an austenitisation temperature of 850 °C with a heating time of 20 minutes was selected. Considering the calculated M_f values, the quenching temperatures were chosen from 200 to 270 °C. The redistribution temperatures were varied from 250 to 400 °C. The proportion of martensite at the quenching temperature f_m was calculated according to the Koistinen-Marburger relation [SPEER 2005]:

$$f_m = 1 - e^{[\alpha(M_s - QT)]}\ [\%] \quad (1)$$

The α term represents the material constant taking the value of - 0.011, the M_s term is the temperature of the beginning of the martensitic transformation depending on the specific chemical composition of the parent untransformed austenite, QT determines the specific quenching temperature of steel below the M_s temperature. The calculated values from equation 1 are shown in Figure 2 [GYHLESTEN BACK 2017]. As the quenching temperature increases, the proportion of martensite decreases and the proportion of residual austenite increases. The higher residual austenite content and its morphology favourably influence the steel's ductility, toughness and, in particular, the formation of envelopes around the martensite needles. The amount of residual austenite is influenced by its stability and austenite grain size [ZHU 2012].

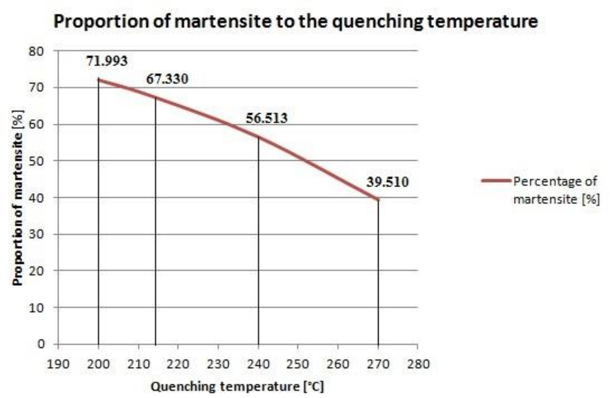

Figure 2. Proportion of martensite to the quenching temperature

The lowest quenching temperature QT of 200 °C was suggested due to the calculated M_f temperature of 197 °C. The highest QT cloud point was proposed based on the 2/5 contribution of martensite formation to the cloud point (Figure 2). The redistribution temperatures were designed such that the minimum difference between the QT quenching temperature and the PT redistribution temperature was 50 °C [KUCEROVA 2014]. The maximum redistribution temperature of 400 °C was designed following the manufacturer's recommendation not to heat SECURE 400 steel to temperatures higher than 400 °C to avoid hardness reduction [YUMPU 2023]. The austenitisation temperature was chosen above the calculated A_{c3} temperature. Table 3 shows the processing parameters selected for the proposed experimental programme. The samples for heat treatment were labelled according to the cloud point and redistribution temperatures - 200/250, 214/290, 240/290 and 270/400. AS135 quenching salt was used as the quenching medium.

Marking of Sample	Temp./Time of austenitisation [°C/min]		Quenching medium	Temp./Time of quenching [°C/sec]		Temp./Time of partitioning [°C/min]	
200/250	850	20	AS 135	200	22	250	10
214/290	850	20	AS 135	214	22	290	10
240/290	850	20	AS 135	240	22	290	10
270/400	850	20	AS 135	270	60	400	15

Table 3. Heat treatment temperatures with Q-P process

After temperature redistribution, sample cooling was performed at RT in free air. [EDMONDS 2011]. The structure of each sample was visualised by chemical etching of the surface in 3% Nital solution and observed using an Olympus GX-51 microscope. Mechanical properties were investigated by an HV10 hardness test, which was performed on a Vickers Wolpert 432-SVD hardness tester and micro-tensile test (M-TT) on an MTS Exceed model E43 universal testing machine. The test specimens were cut in the rolling direction. The M-TT was performed using a special test rig with a high sensitivity load cell. The axial elongation was captured by a high-speed CCD camera [KONOPIK 2018].

RESULT

1.1 Microstructure

After heating the SECURE 400 steel samples and subsequent quenching above Mf temperature, austenite was converted to martensite. Diffusion processes in the material were inhibited by rapid quenching to QT, with the material in an unstable state. This was followed by heating to the redistribution temperature and isothermal hold at this temperature, at which redistribution occurred at the tempering temperatures [KUCEROVA 2016]. Figure 3 shows the martensitic microstructure of the delivered initial state of SECURE 400 steel. The steel was delivered in the quenched state. Carbide particles are visible in the structure. Figures 4 to 7 show the microstructures of SECURE 400 steel after heat treatment using the Q-P process.

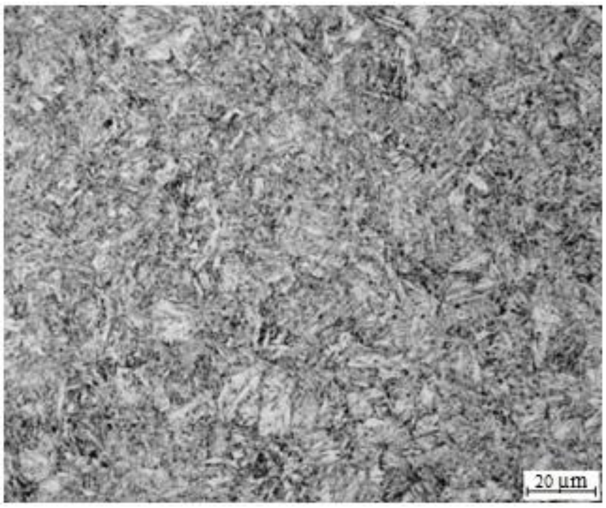

Figure 3. SECURE 400 steel delivered sample

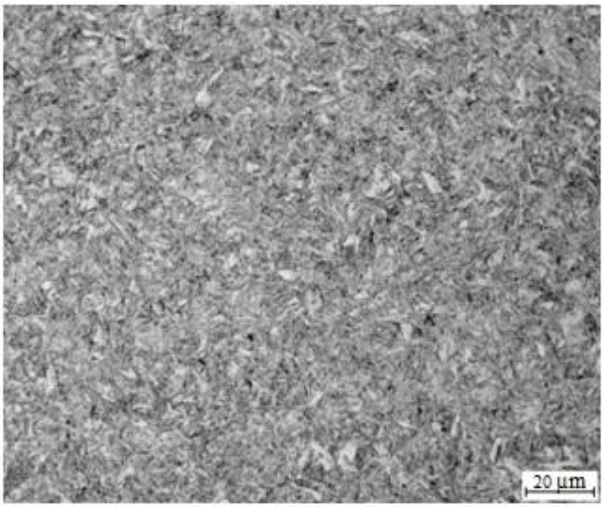

Figure 4. SECURE 400 steel sample after Q-P process 200/250 °C

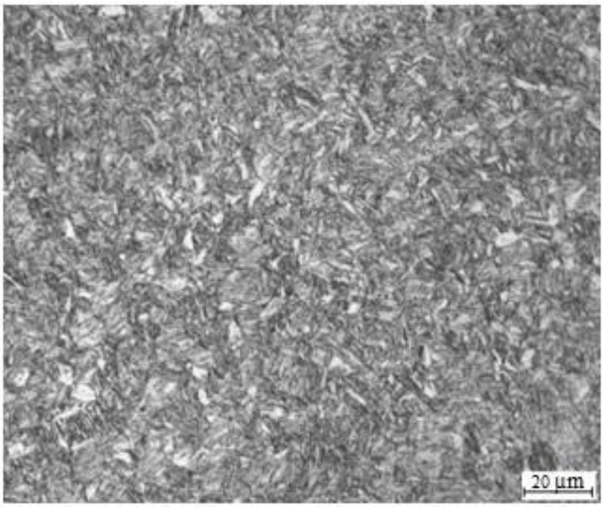

Figure 5. SECURE 400 steel sample after Q-P process 214/290 °C

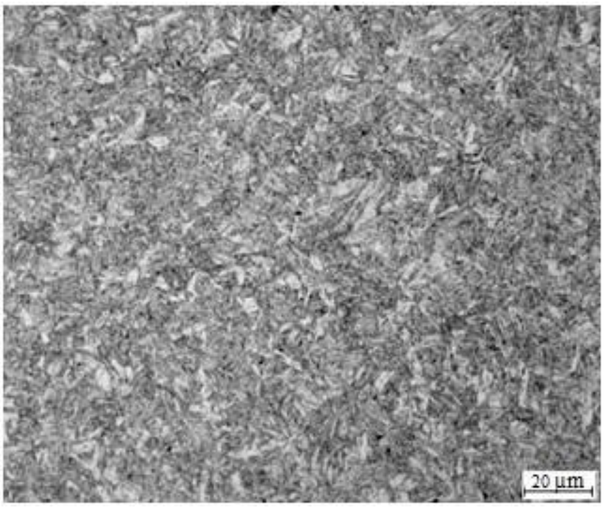

Figure 6. SECURE 400 steel sample after Q-P process 240/290 °C

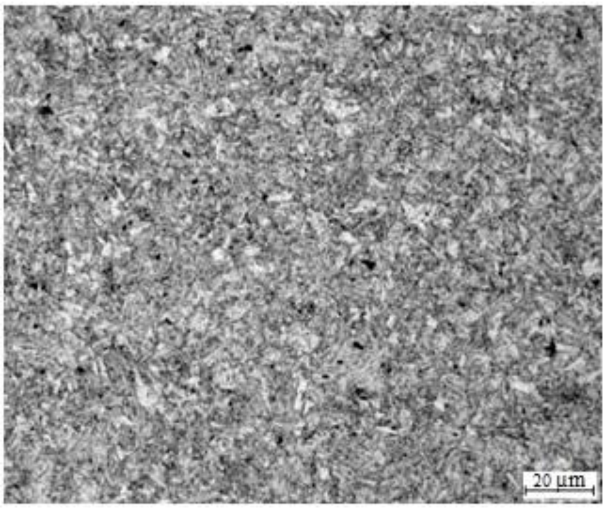

Figure 7. SECURE 400 steel sample after Q-P process 270/400 °C

After heat treatment by the Q-P process, the samples developed a finer grained structure than the microstructure of the original supplied material (Figure 3). According to the graph in Figure 2, the sample 200/250 (Figure 4) has the smallest volume of residual austenite, with approximately 72% martensite formed in the structure when quenched to QT, with the remainder of the structure consisting of residual austenite and carbides. It can be assumed that almost all of the residual austenite was converted to the martensitic phase on cooling from the redistribution temperature to room temperature. In the case of sample 214/290 in Figure 5, dissolution of carbides during austenitisation and subsequent prevention of carbide re-precipitation during processing occurred. According to the graph in Figure 2, approximately 67% martensite was formed in the structure during quenching to QT, with the remainder being residual austenite. Since no carbide formation occurred, all of the remaining 33% residual austenite was involved in the conversion to stabilized austenite during the redistribution and subsequent cooling. According to the graph in Figure 2, the sample 240/290 (Figure 6) formed about 56.5% martensite in the structure when quenched to QT, the rest being residual austenite and carbides. The formation of carbides affects the percentage of residual austenite in the sample that remains in the structure after cooling to RT. This is due to the use of carbon, which is used to stabilise the residual austenite instead of the carbides. According to the graph in Figure 2, for sample

270/400 (Figure 7), about 39.5% martensite was formed in the structure when quenched to QT, the remainder being residual austenite and carbides. A large portion of carbides was found in the structure. Due to the time delay in the quenching, it can be assumed that bainite was formed.

1.2 Mechanical testing

In the mechanical tests, HV10 hardness measurements and, due to the limited amount of material, a micro-tensile test in the longitudinal direction, were performed to determine local properties [DZUGAN 2015]. For each specimen, 3 measurements were performed and the resulting hardness averages were compared with the hardness values of the original specimen (Table 4).

Marking of Sample	Mean HV 10 with standard deviation
Original S400	438±1
200/250	501±9
214/290	452±1.5
240/290	484±8
270/400	470±4.6

Table 4. HV10 hardness test results

The residual (supersaturated) austenite stabilises as the temperature of redistribution is maintained, with higher hardness (Table 4) and strength (Table 5) values being measured. The higher strength values are influenced by the amount of martensite formed in each sample. Based on the standard [ISO 6892-1:2016 2016], micro-tensile tests were evaluated and the measured results are shown in Table 5.

Marking of Sample	Average values		
	R_m [MPa]	$R_{p0,2}$ [MPa]	A [%]
Original S400	1354	1273	18.7
200/250	1654	1212	19.8
214/290	1601	1333	18.1
240/290	1596	1343	17.8
270/400	1436	1326	18.7

Table 5. Mechanical test results

The results show that the Q-P process has an effect on the mechanical properties of SECURE 400 steel. Compared to the supplied original specimen, the 200/250 specimen achieved about 60 HV higher hardness and at the same time the ultimate strength increased by 300 MPa while maintaining almost the same ductility. However, there was a reduction in yield strength of 60 MPa. Specimen 214/290 was found to have the lowest hardness of all the specimens processed, 14 HV lower than the hardness of the original specimen supplied. A hardness approximately 46 HV higher than the hardness of the original specimen was measured for specimen 240/290. Specimens 214/290 and 240/290 showed an increase in ultimate strength and yield strength of about 240 MPa and 60 MPa and 70 MPa respectively, but elongation was reduced by 0.6% and 0.9% respectively. The hardness of specimen 270/400 was found to be approximately 30 HV higher than that of the original specimen supplied, with an increase in ultimate strength of 80 MPa and yield strength of 50 MPa. No changes were observed in the case of ductility. The basic properties of martensite include high strength and hardness, which explains the higher mechanical properties of the samples after the Q-P process. After the Q-P process, there was no significant tempering of the martensitic structure as in the case of the conventional refining process. Since the Q-P process involves the use of stabilised residual austenite, there was no deterioration in ductility. As a result, higher ultimate strength values could be achieved compared to the initial as-delivered condition with comparable ductility values.

CONCLUSION

The Q-P heat treatment of SECURE 400 steel has resulted in an increase in the hardness and strength of the material. The specimen supplied had a tempered martensitic microstructure with carbide particles. The hardness of the sample was measured at 438 HV10. The tensile test determined the ultimate strength to be 1354 MPa, the yield strength to be 1273 MPa and the ductility to be 18.7%. Comparison of the hardness and mechanical properties of the delivered sample and the samples after heat treatment using the Q-P process shows the best result for sample 270/400, which exhibits higher values of strength and hardness while maintaining ductility. Specimen 200/250 shows the highest measured values, except for a lower yield strength value. Specimens 214/290 and 240/290 show increased mechanical property values, apart from the values for ductility, which are lower.

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