OPTIMIZATION OF QUENCHING PROCESS IN HOT STAMPING OF BORON ALLOYED STEEL

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ABSTRACT

This thesis explained the effect of quenching process parameters in hot press forming that has been used in automotive industry to manufacture metallic parts with high specific strengths. Optimum cooling system need to be considered during the quenching process in hot stamping to achieve the highest strength. The material that had been used in this hot press forming process was boron alloyed steel (22MnB5) that will produce the highest martensite content after being hot stamped. After being heated in the furnace up to 950 0C until 10 minutes, the specimens were pressed at 40 bar by using the hydraulic power press and quenched. The investigations were studied on the microstructure and its hardness properties. Every specimen was prepared for the mechanical testing. To get the optimum parameters, ANOVA were used by using the full factorial design. The responses were studied on hardness value. The result shows that by increasing the quenching time and flow rate will increase the hardness value of the specimen while lowering the coolant temperature will increase the hardness value. The heat transfers by conduction were optimum during the pressure holding time process so the optimum cooling systems hardly effect the formation of the blank. The value of hardness are directly proportional with the formation of martensitic microstructure but it was impossible to achieve a fully martensite structure after the blank being hot stamped. The formation of martensite was due to the heating of the blank until its austenite phase and rapid cooling that make the carbon atom stretch along one direction. Besides martensite structure, the formation of bainite and retained austenite structure also appeared after the blank being hot stamped. to achieve an optimum hardness value up to 551.3 HV0.5, the specimen should be quenched at 7 second with the flow rate of 40 L/min and coolant temperature of 27 ^{0}C.

ABSTRAK

Tesis ini menjelaskan kesan proses parameter pelindapkejutan dalam proses pembentukan panas yang telah digunakan dalam industri automotif untuk mengeluarkan bahagian logam dengan kekuatan tertentu yang tinggi. Sistem penyejukan optimum perlu dipertimbangkan semasa proses pelindapkejutan dalam pembentukan panas untuk mencapai kekuatan tertinggi. Bahan yang telah digunakan dalam akhbar panas proses ini membentuk adalah keluli aloi boron (22MnB5) yang akan menghasilkan kandungan martensit tertinggi selepas dicap panas. Selepas dipanaskan dalam api sehingga 950 0C hingga 10 minit, spesimen ditekan pada 40 bar dengan menggunakan akhbar kuasa hidraulik dan dipadamkan. Siasatan telah dikaji pada mikrostruktur dan sifat kekerasan. Setiap spesimen telah disediakan untuk ujian mekanikal. Untuk mendapatkan parameter optimum, ANOVA telah digunakan dengan menggunakan reka bentuk faktorial penuh. Jawapan yang telah dikaji pada nilai kekerasan. Hasil kajian menunjukkan bahawa dengan meningkatkan masa pelindapkejutan dan kadar aliran akan meningkatkan nilai kekerasan spesimen manakala merendahkan suhu penyejuk akan meningkatkan nilai kekerasan. Pemindahan haba secara pengaliran adalah optimum semasa tekanan induk masa proses supaya sistem penyejukan optimum tidak memberi kesan pembentukan kosong. Nilai kekerasan adalah berkadar langsung dengan pembentukan mikrostruktur martensit tetapi ia adalah mustahil untuk mencapai satu struktur martensit sepenuhnya selepas spesimen yang dicap panas. Pembentukan martensit adalah disebabkan oleh pemanasan spesimen sehingga fasa austenit dan penyejukan pantas yang membuat menjulurkan atom karbon di sepanjang satu arah. Selain struktur martensit, pembentukan bainit dan sisa austenit juga muncul selepas spesimen yang dicap panas. Untuk mencapai nilai kekerasan optimum sehingga 551,3 HV0.5, spesimen perlu dipadamkan pada 7 saat dengan kadar aliran 40 L / min dan suhu penyejuk daripada 27 ^{0}C.

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LIST OF SYMBOLS

^0C	Degree celcius
$^0C/s$	Degree celcius per second
K/s	Kelvin per second
s^{-1}	Per second
%	Percent
g	Gram
α	Angle of indenter
MPa	Megapascal
Gpa	Gigapascal
22MnB5	Boron alloyed steel
mm	Milimetre
s	Second
L/min	Litre per minute
psi	Pound per square inch
rpm	Revolution per minutes
kPa	Kilo pascal
$HV_{0.5}$	500kPa Vickers hardness unit
m/s	Metre per second
VS	Versus
df	Differentiation
Ac1	Austenite start temperature

Ac3	Start temperature of primary ferrite to austenite transformation
Ms	Martensite start temperature
Mf	Martensite finish temperature
N/mm^2	Newton per millimeter square

LIST OF ABBREVIATIONS

Al	Aluminum
ANOVA	Analysis of variance
B	Boron
C	Carbon
CCT	Continuous cooling transformation
Cr	Chromium
LOM	Light Optical Microscopy
Mn	Manganese
N	Nitrogen
Ni	Nickel
UHSS	Ultrahigh-strength steels

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

The demand in automotive industry to reduce the vehicle weight while considering the safety have rapidly increase the manufacturing of lightweight body parts from ultrahigh-strength steels (UHSS). The process of forming this ultrahigh-strength steel is limited by low formability and considerable spring back. To overcome this problem, an alternative solution has been made by using the hot stamping. There are two methods that have been introduced for hot stamping process which is direct and indirect hot stamping. The advantages of hot stamping process are providing better formability at high temperature. This not only make it easy to form but also no spring back happen at the final part. Hot stamping process on boron alloyed steel (22MnB5) also take advantage of low flow stress in austenitic phase at elevated temperature. Hot stamping was developed and patented in 1977 by a Swedish company (Plannja), which uses the process for saw blades and lawn mower blades. In 1984, Saab Automobile AB was the first vehicle manufacturer who adopted a hardened boron steel component for the Saab 9000 [2]. The number of produced parts increased from 3 million parts per year in 1987 to 8 million parts per year in 1997, which further increased to approximately 107 million parts per year in 2007 [3].

1.2 PROBLEM STATEMENT

One of the most important social demands in the sheet forming industry is the forming of automotive part with high strengths and lightweight steel parts. But such parts exhibit poor elongation that sacrifices formability in the cold state. Thus, the cold forming of high-strength steel sheets with a tensile strength of 1 GPa has been regarded as unrealistic for some time. Also, sheet metal forming at elevated temperatures has low strength and uneven microstructure. But, if a hot-formed blank is quenched by heat conduction to the dies used in forming, lightweight metallic parts with strength higher than 1.5 GPa could be formed without serious difficulties. In quenching process, optimum cooling systems need to be considered during the quenching process to achieve the highest strength. Thus, optimizations of the cooling system during the hot stamping process were studied in this project.

1.3 OBJECTIVE OF THE STUDY

The objectives of this study were;

- To investigate the effect of quenching parameters on mechanical properties and microstructure of boron alloyed steel in hot press forming,
- To produce a high strength boron steel by optimization using experimental design.

1.4 SCOPE OF THE STUDY

The scopes of this study were;

i) Sample preparation of boron alloyed steel (22MnB5),
ii) Develop design of experiment (DOE) for hot press forming of boron alloyed steel,

iii) Conduct hot press forming of boron alloyed steel using DOE,

iv) Characterization of HPF samples for hardness properties and metallographic study,

v) Optimization of hot press forming for maximum hardness by using Design Expert software.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

The main purpose of this chapter is to provide a review of past research efforts related to hot stamping process, including the effect of heating temperature on mechanical properties of hot formed steel sheet metals and the influence of the process parameters such as punch speed, punch stroke, soaking time, initial deformation time, and temperature of coolant. This chapter also includes the review over the research on hardenability and microscopy. Finally, this chapter will introduce the method for design of experiment. This starts with the description of the work piece material used in hot stamping. Then, the process steps of hot stamping are described with details.

2.2 HOT STAMPING PROCESS

2.2.1 Historical Perspective

Due to the demand for reduced vehicle weight, improved safety, and crashworthiness qualities, the need to manufacture automobile structural components from ultra-high strength steels is apparent [7]. This is because one of the most important social demands in the industry is the forming of metallic sheets with high specific tensile strengths into lightweight metallic parts. One of the companies from Swedish named ‘Planja Company’ designed the hot stamping process that is used for saw blades and lawn mower blades and then in 1984, Saab Automobile AB as the first vehicle

manufacturer has adopted a hardened boron steel component for the Saab 9000 [2]. After that, the part that is produced by the boron steel increased dramatically. Since 21st century, more hot stamped parts have been used in the cars and the number of produced parts/year has gone up to approximately 107 million parts/year in 2007 [3]. There are two methods that have been introduced for hot stamping process which is direct and indirect hot stamping.

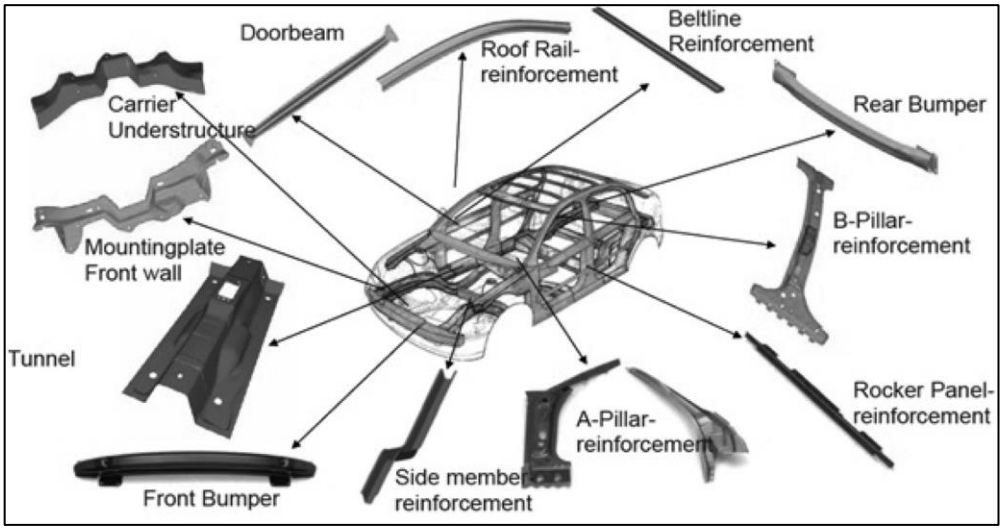

Figure 2.1 Hot stamped part [7].

2.2.2 Direct Method

In the direct method, the blanks are austenitized at temperatures between 900 and 950 ^{0}C for 4 to 10 minutes inside a continuous-feed furnace or by using conduction heating and subsequently transferred to an internally cooled die set via a transfer unit [5]. The transfer usually takes less than 3 seconds to avoid temperature drop and to avoid the martensite phase transformation. At high temperature between 650 to 850 ^{0}C, the material has high formability, and complex shapes can be formed in single stroke. The blanks are stamped and cooled down under pressure for a specific amount of time according to the sheet thickness after drawing depth is reached. During this period, the formed part is quenched in the closed die set that is internally cooled by water

circulation at a cooling rate of 50 to 100 ^{0}C/s, completing the quenching (martensitic transformation) process. The total cycle time for transferring, stamping, and cooling in the die is 15 to 25 s. The part leaves the hot stamping line at approximately 150 ^{0}C and with high mechanical properties of 1400 to 1600 MPa and yield strength between 1000 and 1200 MPa.

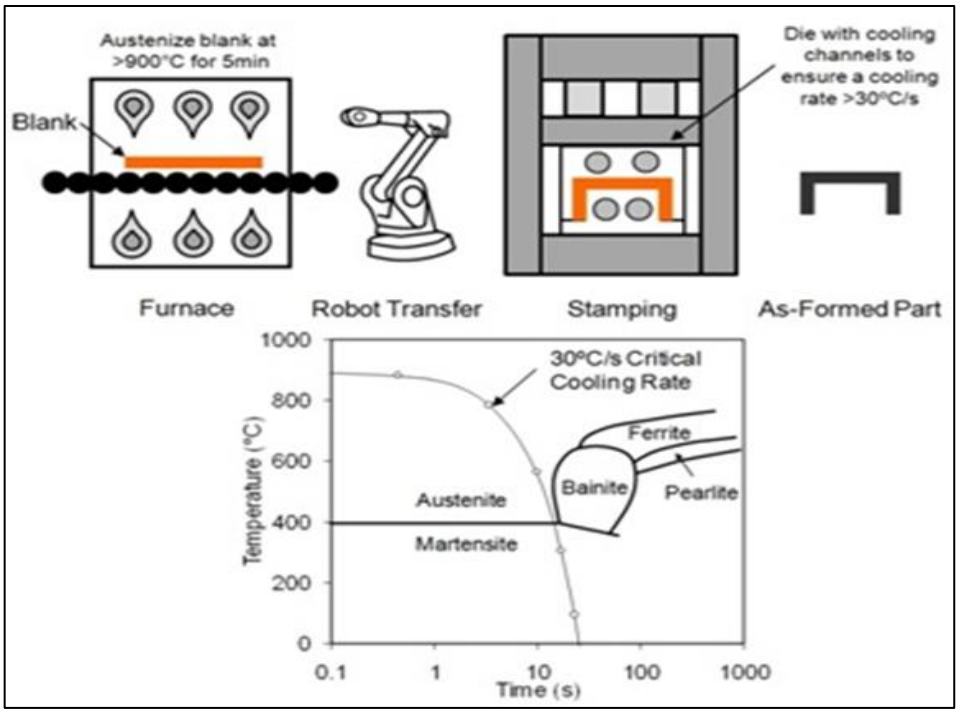

Figure 2.2 The direct hot stamping method [5].

2.2.2 Indirect method

The differences between the indirect method and direct method is indirect hot stamping provides a part to be perform first about 95% of its final shape in conventional press die [7]. Then, the part is heated in a continuous furnace until its austenitization temperature. Finally, the blank is transferred to the hot press machine and being formed again for the final shape. The reason for the final step is to extend the forming limits for very complex shapes by hot forming and quenching the cold formed parts.

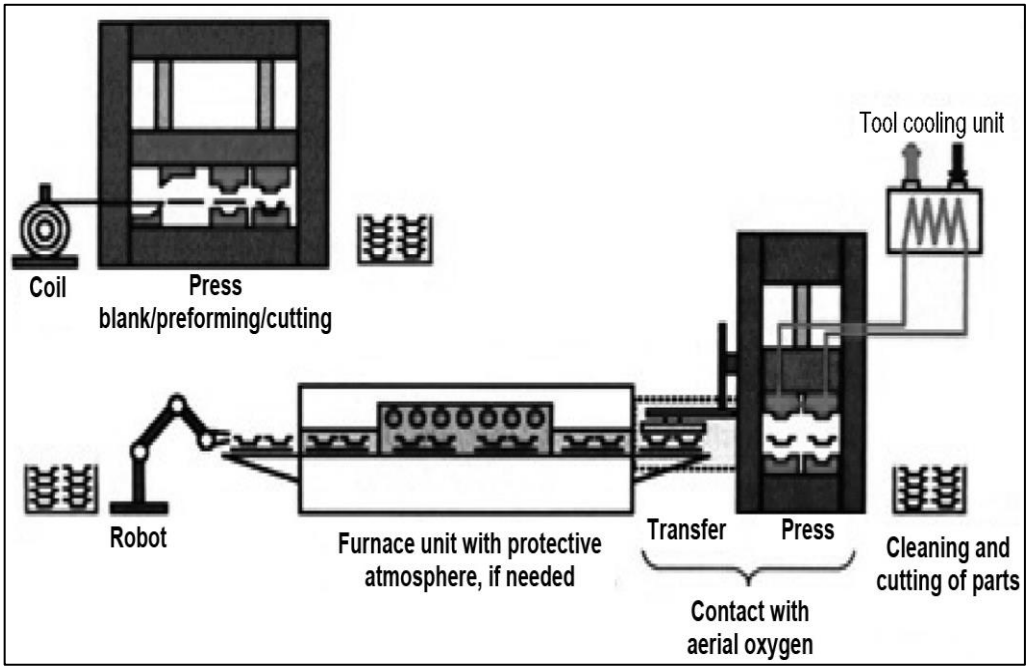

Figure 2.3 The indirect hot stamping method [7].

2.2.3 Blanks

The steel grades which can produce fully martensitic microstructure after hot stamping are boron alloys of 22MnB5, 27MnCrB5, and 37MnB4 steel grades as shown in Table 2.1 [1].

Table 2.1 Chemical components of boron steel [1].

Steel	Al	B	C	Cr	Mn	N	Ni	Si	Ti
20MnB5	0.04	0.001	0.16	0.23	1.05	-	0.01	0.40	0.034
22MnB5	0.03	0.002	0.23	0.16	1.18	0.005	0.12	0.22	0.040
8MnCrB3	0.05	0.002	0.07	0.37	0.75	0.006	0.01	0.21	0.048
27MnCrB5	0.03	0.002	0.25	0.34	1.24	0.004	0.01	0.21	0.042
37MnB4	0.03	0.001	0.33	0.19	0.81	0.006	0.02	0.31	0.046

The addition of boron into the steel alloy lowers the critical cooling rate and therefore extends the process window. Furthermore, alloying boron reduces the carbon equivalent and therefore increases the weldability [11]. Chrome and manganese increase the tensile strength of the quenched material [11].

Based on the Table 2.2, 22MnB5 steel grade is the most commonly used in hot stamping process. The indicated finish temperature is not related to the 100% martensite formation. So, there is no possibility for the boron alloyed steel to have a fully martensitic microstructure. Table 2.2 show that martensite starts and finish temperatures, M_s and M_f, are 410 and 230 ^{0}C. Yield stress as delivered is 457 MPa and after hot stamped is 1010 MPa. Finally, its tensile strength as delivered is 608 MPa and after hot stamped is 1478 MPa. The microstructure of boron alloyed plate before it is being hot stamped is consisting of ferrite and pearlite [11]. The first temperature at which austenite start temperature (Ac1) is 720 ◦C, the start temperature of primary ferrite to austenite transformation (Ac3) was determined to be 880 ◦C [11].

Table 2.2 Mechanical properties of boron steel [1].

Steel	**Martensite start temperature in ^{0}C**	**Critical cooling rate in K/s**	**Yeild stress in MPa**		**Tensile strength in MPa**	
			As delivered	**Hot stamped**	**As delivered**	**Hot stamped**
20MnB5	450	30	505	967	637	1354
22MnB5	410	27	457	1010	608	1478
8MnCrB3	-	-	447	751	520	882
27MnCrB5	400	20	478	1097	638	1611
37MnB4	430	14	580	1378	810	2040

Most boron steel grades are usually applied in car chassis parts. The advantages of the hot stamping process of the boron steel are [14];

- very high formability during hot forming,
- forming of very complex geometries,
- producing of ultra-high strength steel parts,
- high toughness,
- independence of material properties on the forming depth,
- acceptable dimensional tolerances,
- good weldability and
- crash application.

2.2.4 Heating of Blank

The first process in hot stamping is the heating of the blank up to its austenitization temperature. At a furnace temperature of 950 ^{0}C, a dwell time of 10 minutes was found to be sufficient to obtain the maximum martensitic content in the quenched samples with a maximum hardness of approximately 470 $HV_{0.5}$ [7]. This finding agrees with Ankara [4] observations. They state that the lath shaped martensite transformation is commonly linked with grain boundaries. Based on this, the longer austenitization soaking time resulted in a coarser primary austenite grain size. In the other word, increasing the soaking time will lower the martensite start temperature. Besides that, increasing the furnace temperature will decreased the austenitization duration time. This is because at a higher deformation temperature, the blank are at above the zone of bainitic and ferritic phase transformations [11]. The possibility to avoid bainite and ferrite will increase while the volume of martensite will increase. When the blank is in contact with the air under austenitization conditions, oxide scale formation will occurs immediately. To avoid surface oxidation and decarburization during the direct hot stamping operation, most blanks are pre-coated with protective layer [8].

2.2.5 Forming

Each sample was cooled down to the initial deformation temperature. Blank must be transferred as quickly as possible from the furnace to the press machine in order to avoid cooling of the part before forming [7]. Furthermore, forming must be completed before the beginning of the martensite transformation. In order to avoid the quenching of the blank between the blank holder and the die during the forming process, most of the hot stamping tool systems work with a distance blank holder [7]. The cooling process as a working media is also important in the forming process. The use of temperature as a process parameter in hot gas forming and a simultaneous quenching of the formed parts offer the opportunity to increase the application field of this innovative technology [9]. A homogenous blank temperature distribution leads to a uniform forming of the blank because of the lower contact time between the part and the tool during forming.

The most important parameter in the hot stamping process is the applied force and this force can be controlled and monitored by the load cell on the punch [11]. The punching force is controlled by using the hydraulic servo unit system. It was observed that the higher applied forces lead to more secondary phase formation [11]. This means that it will tend to decrease the martensite start temperature and the dislocation density of the austenite matrix will increases.

From Figure 2.4(a), we can see the flow of the hot stamping process corresponding to surface hardness calculation performed by M. Naderi. It takes around 10 minutes to complete the process and the graph also shown the variation of martensite starts and finish temperature by hardness measurement. It shows that martensite start temperature is at 410 ^{0}C while the martensite finish temperature is at 230 ^{0}C. Figure 2.4(b) show the variation of dilatation curve by force. The martensite content is decreased by increasing the driving force.

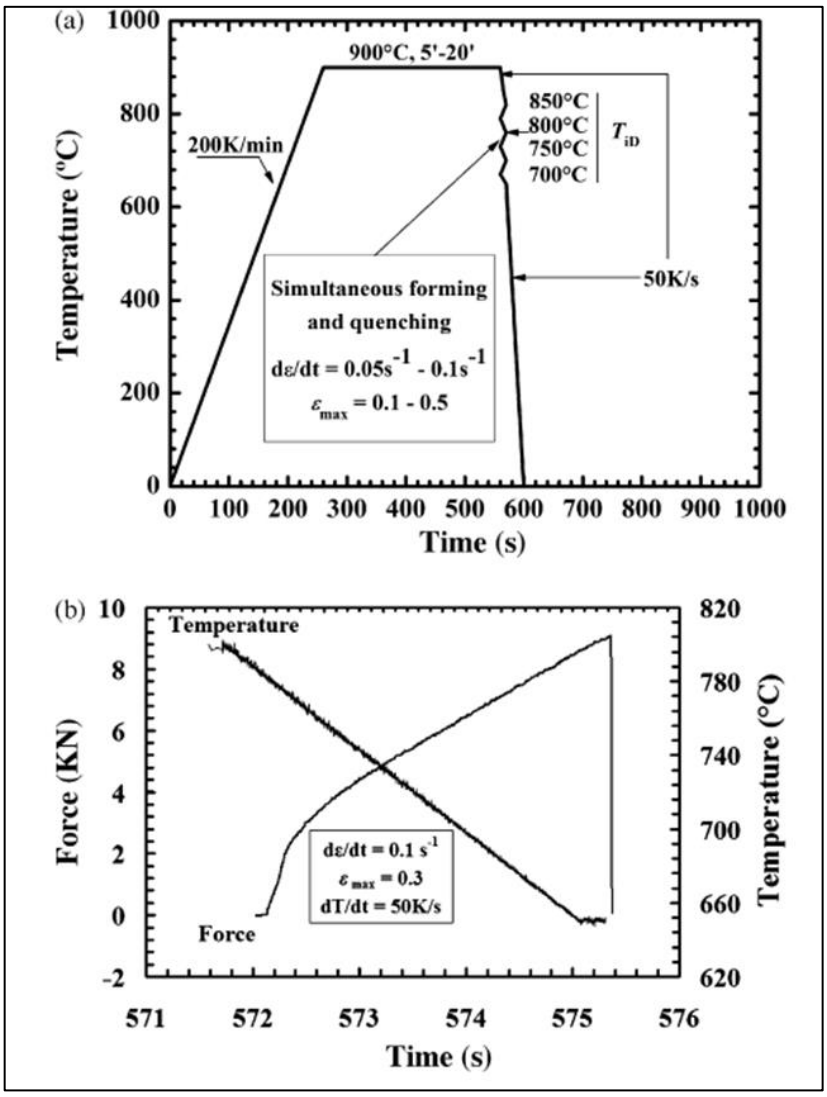

Figure 2.4 The effect of applied force on phase transformations [11].

2.2.6 Quenching

After the blank achieved its austenitic temperature range, it is quenched in the closed tool until the entire martensite transformation of the part is complete. A cooling rate of more than 27 K/s is necessary for a full martensite microstructure of 22MnB5 [7].

Approximate cooling rate can be achieved based on the Continuous Cooling Transformation (CCT) diagram. This CCT diagram was plot based on hardness

measurements, metallographic investigation and by dilatometry tests. From CCT diagram, higher cooling rates do not essentially result in a higher amount of martensite due to the continuation of deformation into lower temperatures, which enhances the possibility of bainitic transformation [11]. This is because when the steel is cooled down rapidly, the phase transformation will not turn to fully martensitic microstructure but it will reform into ferritic and bainitic microstructure. Increase in volume due to the transformation from austenite into martensite will influences the stress distribution during quenching [7]. Transformation from austenite into martensite will decrease the grain size and this will increase its stress. A volume will change due to the different lattice structure of pearlite, bainite, ferrite, austenite, and martensite during the isotropic transformation strains. This effect causes only a change in volume, like the thermal strain increment.

The next subsystem is the die with active control of the heat flux from the hot sheet such that heat is drawn by the blank by contact heat conduction to the die [5]. To change the heat flux from the specimen to the die, or the cooling rate of the hot sheet, a water-cooling channel is dug inside the die metal, and the coolant that flows inside this channel removes the heat from the die. The warm coolant that flows out of the die is cooled again by the chiller and again flows into the channel of the die. Also, the die metal is changed to control the heat conduction. For measuring temperature in experiment, K-type thermo-couple of diameter 0.2mm is welded at the thickness and length center of specimen, width edge of specimen and bottom of punch, as are shown in Figure 2.5 by red solid symbols [5].

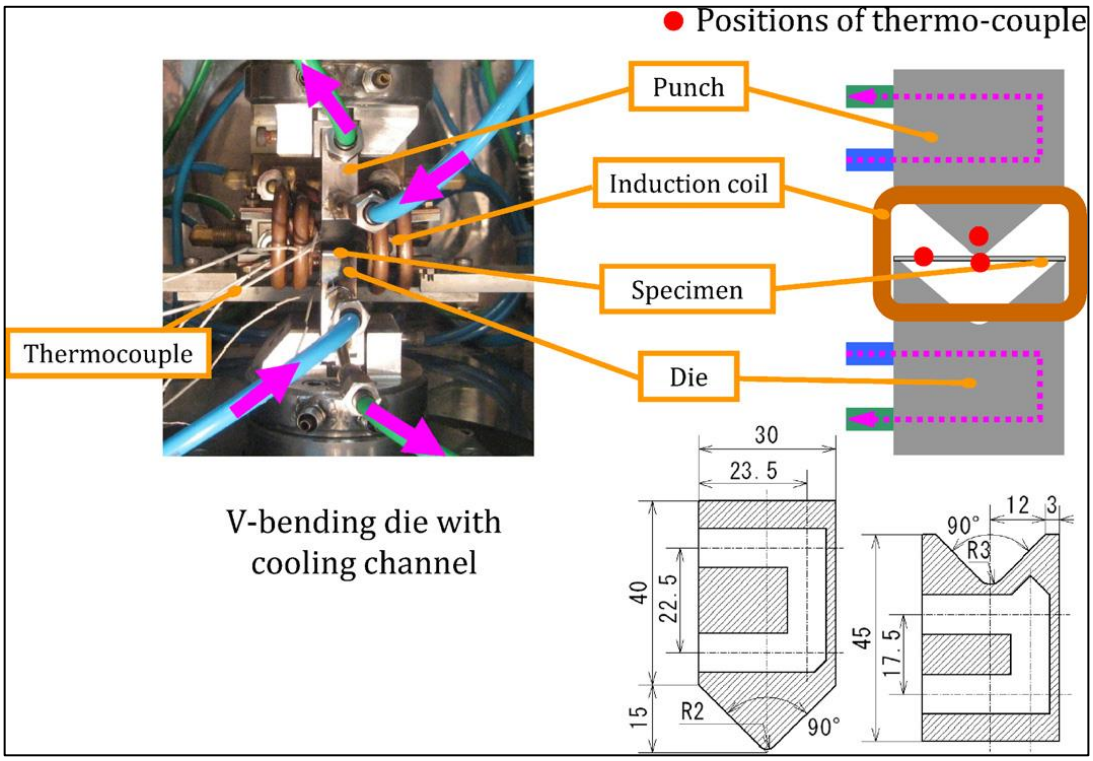

Figure 2.5 Position of the thermocouple and die cooling channel [5].

The function of the cooling duct is to quenched the hot blank effectively until it reach a specific cooling rate while transform into martensite microstructure. Also, the die metal is important to control the heat conduction.

Another important factor with respect to heat drain is the design of the cooling ducts, which is defined by the size, location, and distribution of the cooling ducts [7]. This chiller system is used as a working media for the cooling system in the hot stamping process. There are several type of coolant that can be used which is water, air, hydrogen gas, and salt water. For the economical cooling system, using water as a fluid coolant is the best way [7].

The continuous cooling transformation curve (CCT) illustrates the micro structural evolution of a particular material depending on the cooling rate. In order to reach tensile strength up to 1600 MPa of the final part, a complete transformation of the

austenitic to martensitic microstructure is required [16]. Therefore, cooling rates faster than 27K/s in the part have to be achieved to avoid bainitic or even ferritic- perlitic transformation, as shown in Figure 2.6.

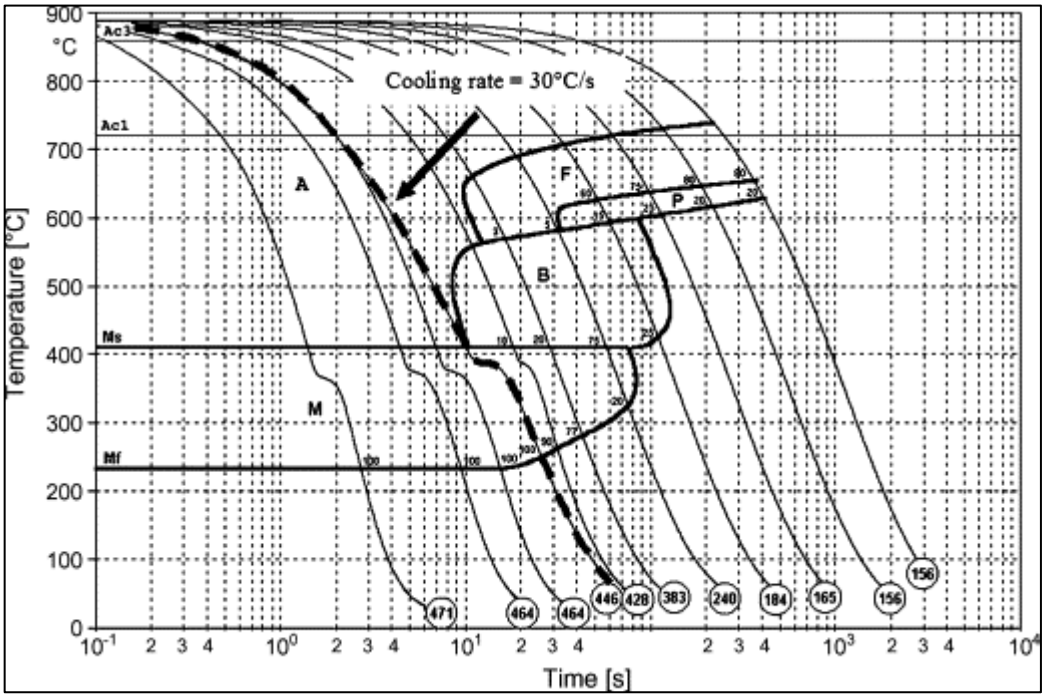

Figure 2.6 Continuous cooling transformation diagrams [[7].

Higher temperature during the process will increase the formation of pearlitic microstructure [13]. From the CCT diagram, lower the cooling temperature also will diffuse out the carbon's atom and will result into the transformation of pearlitic microstructure.

2.3 MECHANICAL PROPERTIES AND MICROSTRUCTURE OF BORON ALLOYED STEEL

2.3.1 Hardness Properties

Hardness is up to which a material is hardened after the process of stamping and it is one of the important criterions in evaluating quenchability [5]. It is a sign on how deep a hardness can be achieve in a certain material. Lechler and Merklein [12] state that the hardness of the boron alloyed steel can be evaluated using the Vickers hardness measurement and to obtain an optimum hardness of 470HV, it must be austenitized at 950 ^{0}C for 3 minutes. Microscopic hardness is defined by strong intermolecular bond. Microscopic hardness tests can be performed on polished samples, taken from the vertically cut cross section of the blank, by using a programmable hardness test machine. Some important elements which will affect the hardness value of boron alloyed steel are [14];

- Austenitizing time and temperature,
- Austenite grain size,
- Pre-forming and heat treatment,
- The other alloying elements.

The hardness properties increase with increasing austenite grain size, because the grain boundary area is decreasing. This means that the sites for the nucleation of ferrite and pearlite are being reduced in number, with the result that these transformations are slowed down, and the hardness is therefore increased. If the percentage of carbon is higher, the boron hardenability effect will decrease. Boron is most effective in increasing the hardenability of low carbon steels and does not take effect in steel with carbon content higher than 0.8 percent. Boron is usually added to increase the hardenability of low carbon steel.

2.3.2 Microstructure

The as-delivered microstructure of boron alloyed steel is consisting of ferritic-pearlitic microstructure [15]. Figure 2.7 below shows the grain structure of 22MnB5 blank before the process of hot stamping. This structure was caused by cold rolling process.

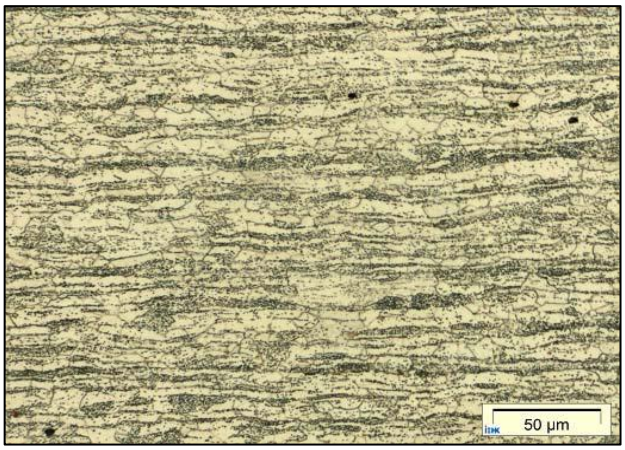

Figure 2.7 Microstructure of the as-delivered 22MnB5 steel [15].

After the boron alloyed steel being heated until it reaches its austenitization temperature, its crystal structure will change. The austenitization temperature not only influences the grain growth in the microstructure, but also increases the retained austenite grain size [15]. This means that taking too long austenitization time will increase the retained austenite grain structure after the quenching process. During rapid cooling, austenite structure becomes mechanically unstable. Due to the fast cooling, diffusion of carbon is restricted. To make room for the carbon atoms, the lattice stretches along one crystal direction. The crystal structure from face-centered cubic will transform into body-centered tetragonal [18]. Due to the high lattice distortion, martensite has high residual stresses. The high lattice distortion induces high hardness and strength to the steel.

Figure 2.8 shows the comparison of microstructure between the blank that is being heated at different temperature.

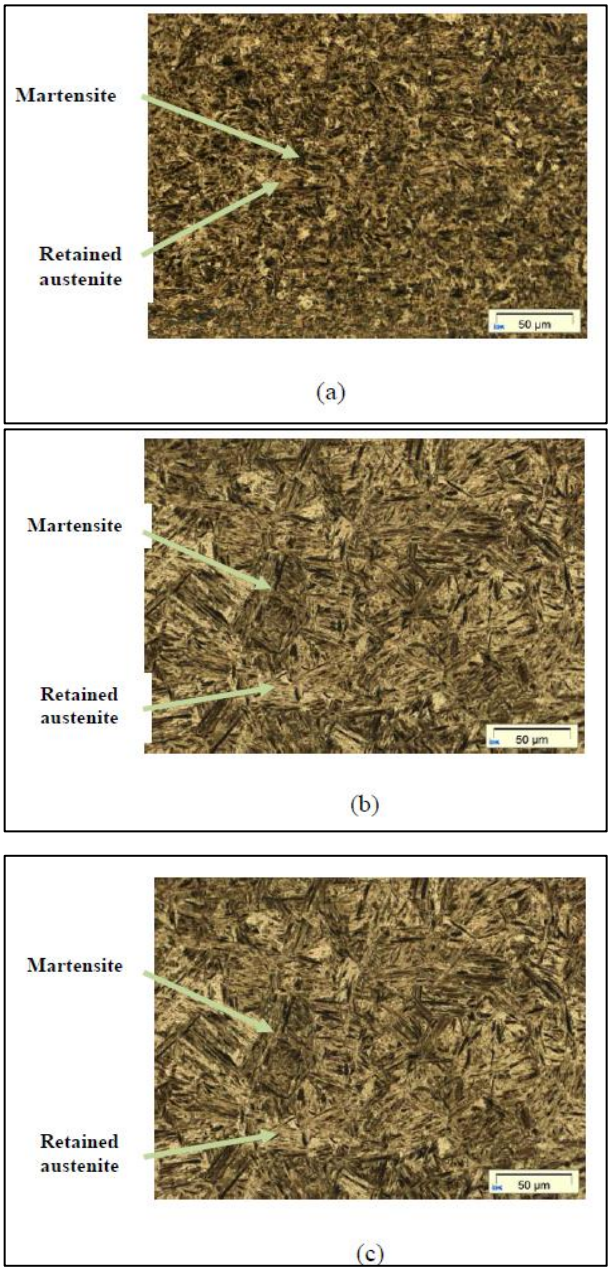

Figure 2.8 Comparing the microstructures of 22MnB5 after austenitizing and quenching with, (a) the austenization temperature of 900°C, (b) the austenitization temperature of 1100°C, and (c) the austenitization temperature of 1200°C [15].

Abbasia et al. [13] investigate the effect of isothermal hot deformation process parameters based on Light Optical Microscopy (LOM). In the investigated steel, the hardness values more than 400–450 and 250–300 $HV_{0.8}$ were related to martensite and bainite phases, respectively, while the hardness values less than 250 HV0.8 were attributed to ferrite phase [13].

From the Figure 2.9 and Figure 2.10, we can see the microstructure and hardness maps of the samples deformed at 900 ^{0}C (strain rate of 1.0 s^{-1}) and at 650 ^{0}C (strain rate of 0.1 s^{-1}). In the second case, we can see the traces of ferrite, bainite and martensite phase while a fully martensite microstructure is characterized in the first sample. This is because of at higher deformation temperatures, the blank is located well above the zone of bainitic and ferritic phase transformations [13]. The crystalline microstructure of boron alloyed steel can be studied by examining it under a microscopic microstructure. This microscope can observe the microstructure of boron alloyed steel in all phase transformation (austenite, martensite, bainite, ferrite and pearlite).

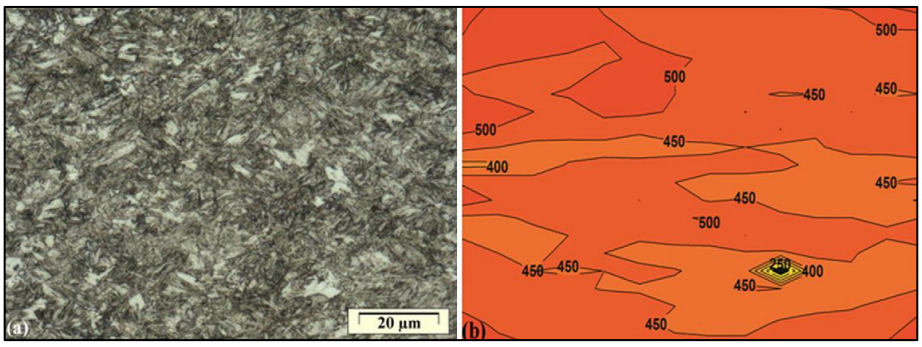

Figure 2.9 (a) Microstructure and (b) hardness map of the specimen deformed at 900^{o}C with strain rate of 1.0 s^{-1} [13].

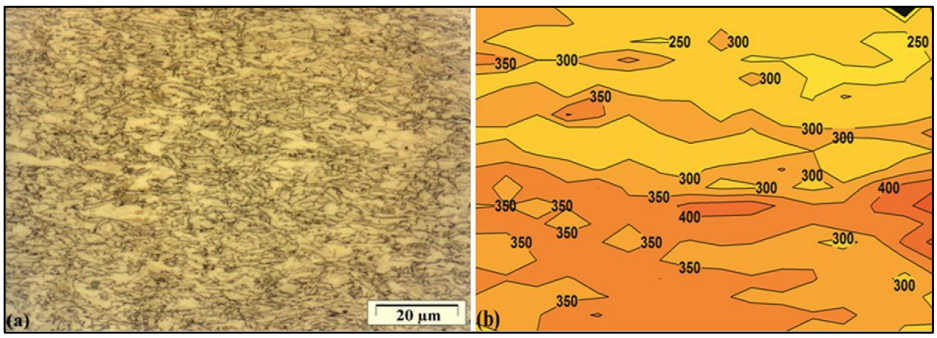

Figure 2.10(a) Microstructure and (b) hardness map of the specimen deformed at 650^{o}C with strain rate of 0.1 s^{-1} [13].

According to the Figure 2.11 below, with the austenitization temperature 900^{o}C, it is not enough to form a microstructure completely martensite compared to 950 ^{0}C austenitization temperature, the formation of martensitic microstructure at the final part is higher.

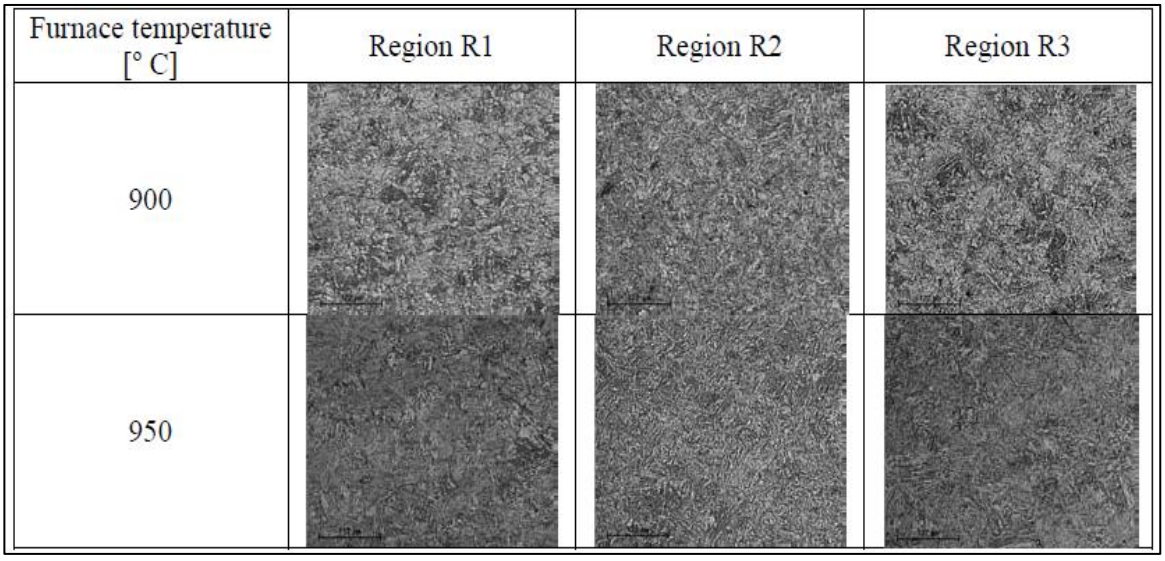

Figure 2.11 Microstructure of hot stamped and cooled samples (Nital 2% and 500X) [15].

2.4 ANALYSIS OF VARIANCE (ANOVA)

The analysis of variance is used to investigate the relationship between the parameters and the response variable, identify the important factors in a process, identify and fix the problem in a process, and also identify the possibility of estimating interactions [19]. This statistical model used to analyze the variation between the variable. ANOVA can be analyzed whether by using the Taguchi or Full Factorial Design.

2.4.1 Two-level Full Factorial Design of Experiment

Two level factorial means two levels of each factor will be studied at once. If there are k factors that we need to evaluate in a process we need to run the experiment 2k times. Each factor will have two levels, a “high” and “low” level. Table 2.3 shows the factorial design in a standard order matrix.

Table 2.3 Factorial design

FACTOR A	FACTOR B	TREATMENT COMBINATION
+	_	A high, B low
_	_	A low, B high
+	+	A high, B high
_	+	A low, B high

Source: Montgometry (2000)

CHAPTER 3

METHODOLOGY

3.1 INTRODUCTION

This chapter provides the preparation of the material, the process of hot press forming, statistical analysis, and testing of hardness properties and microscopy of the materials.

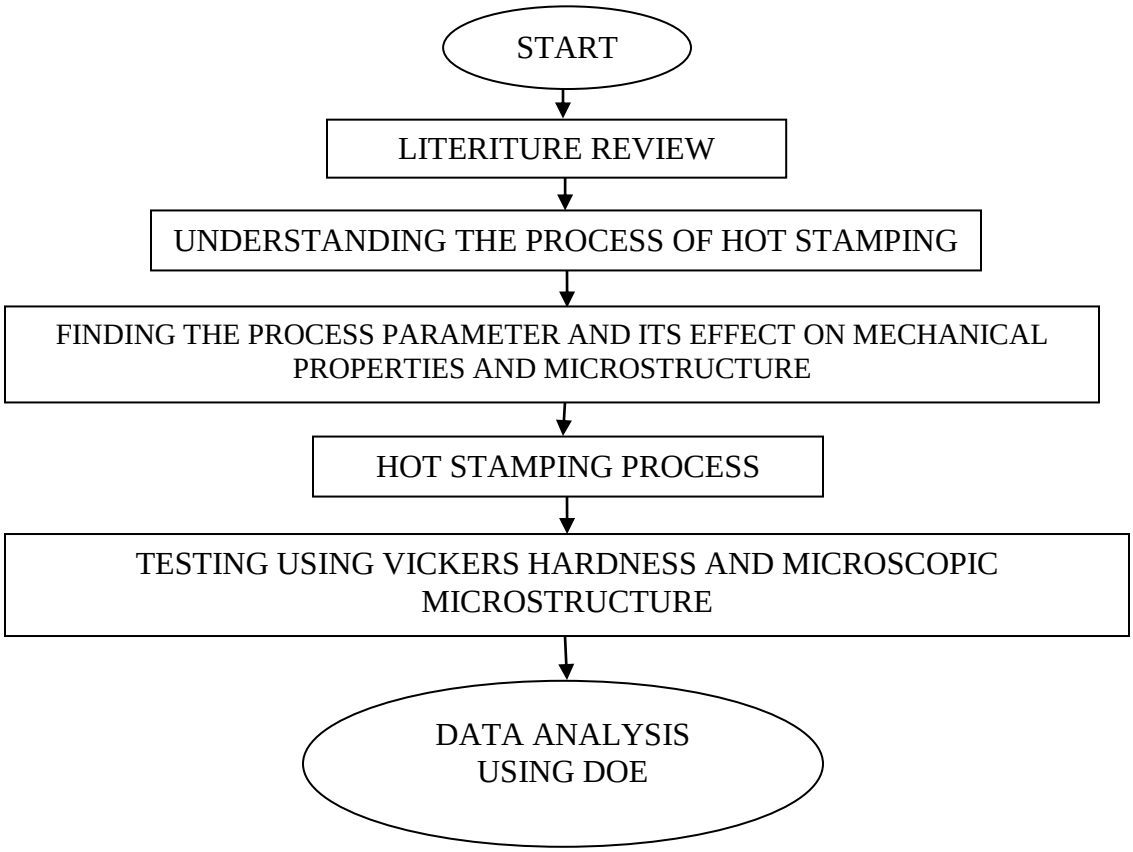

Figure 3.1 Flow chart of methodology

3.2 MATERIAL

The investigated material was boron alloyed steel (22MnB5) processed to as hot boron steel plates. Boron alloyed steel has an ability to produce a fully martensitic microstructure after being quenched. The chemical composition of boron alloyed composed of 0.03 Al, 0.002 B, 0.23 C, 0.16 Cr, 1.18 Mn, 0.005 N, 0.12 Ni, 0.22 Si, and 0.04 Ti [1]. This ultrahigh-strength steel comes with a ferritic-pearlitic microstructure before the processes of hot stamping have been done [7]. Heating this blank will change its crystal structure to austenite phase. When the temperature decreased by rapid cooling, blank's carbon atom do not have time to diffuse out of the crystal structure which result into transformation of martensite microstructure [7]. This forming part has higher tensile strength and hardness. The dimension of the specimen used for this experiment was 60mm X 50mm X 10mm as shown in the Figure 3.2 below.

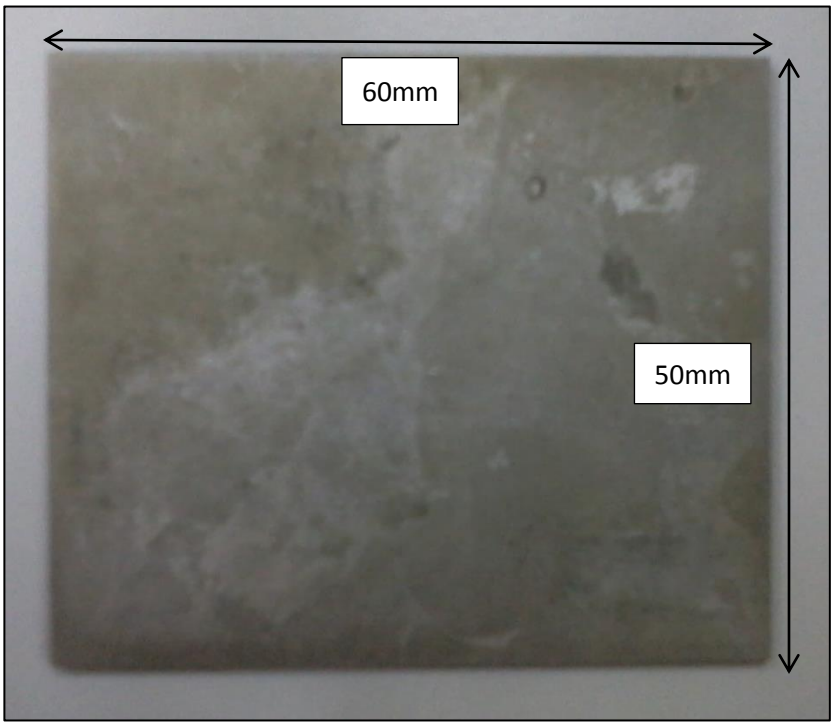

Figure 3.2 Boron alloyed steel plate (22MnB5).

3.3 PROCESS OF HOT PRESS FORMING

The investigation on boron alloyed steel by direct hot stamping process was done by using a hydraulic power press machine. Firstly, the blank were heating in a furnace until it reached its austenitization temperature. At a furnace temperature of 950 ^{0}C, a dwell time of 10 minutes, a fully martensitic microstructure will be formed [5]. After the blank is austenitized, it was transformed into a hydraulic power press machine as quickly as possible to avoid cooling of the part before forming process. The punching force was set as constant by setting the hydraulic servo unit at 40 bar. The blank was set at 800 ^{0}C before its deformation process. The temperature of the blank was detected by using the K-type thermocouple (0.1mm) which was attached inside the die. During this period, the formed part was quenched in the closed die set that is internally cooled by water circulation at a cooling rate of 27 ^{0}C/s, completing the quenching (martensitic transformation) process. Three parameters were controlled during this quenching process which was quenching time, flow rate of the coolant, and coolant temperature. The total cycle time for transferring, stamping, and cooling in the die was 15 to 25 s. The part leaves the hot stamping line at approximately 150 ^{0}C and with high mechanical properties.

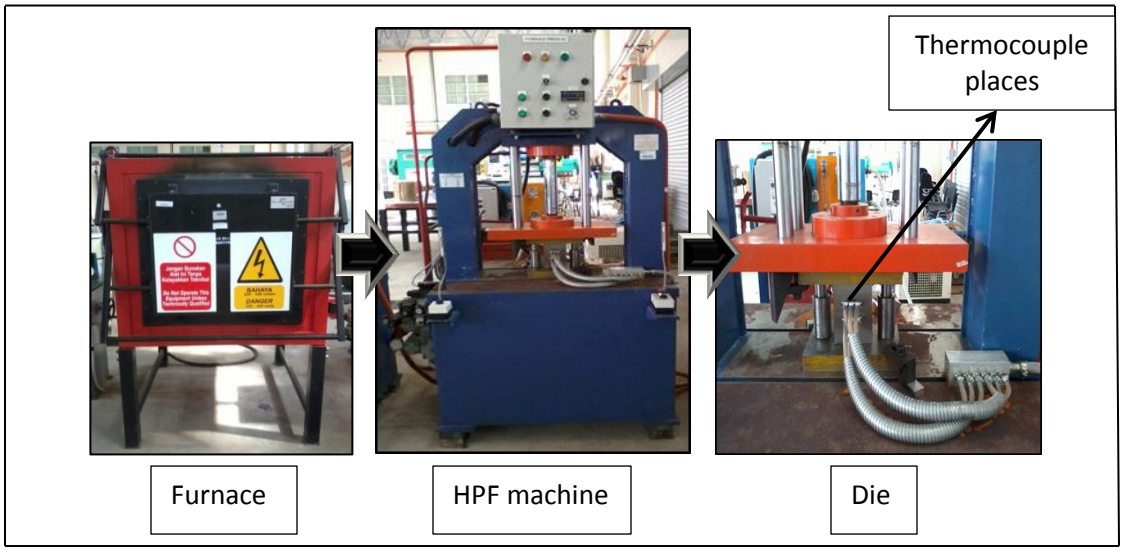

Figure 3.3 Process of hot press forming.

3.4 CONTROL PARAMETER

There are 3 variables that have been controlled during quenching process to investigate their effect on hardness and microstructure. The control parameters were press holding time, flow rate of the coolant, and temperature of the cooling medium.

3.4.1 Press Holding Time

While the force was applied to the blank during the forming process, the holding time was set at 3, 5 and 7 second. The quenching time was controlled by using the control panel as shown in the Figure 3.4 below.

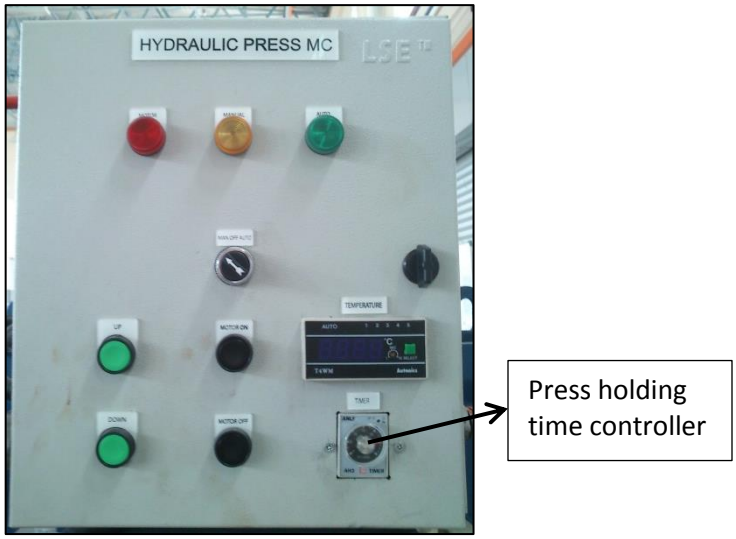

Figure 3.4 Control panel

3.4.2 Temperature of Cooling Medium

Temperature of water was controlled by adding an ice into chiller reservoir to lower the water temperature. The cooling medium was set at ambient temperature (27 ^{0}C), 15 ^{0}C, and 5 ^{0}C.

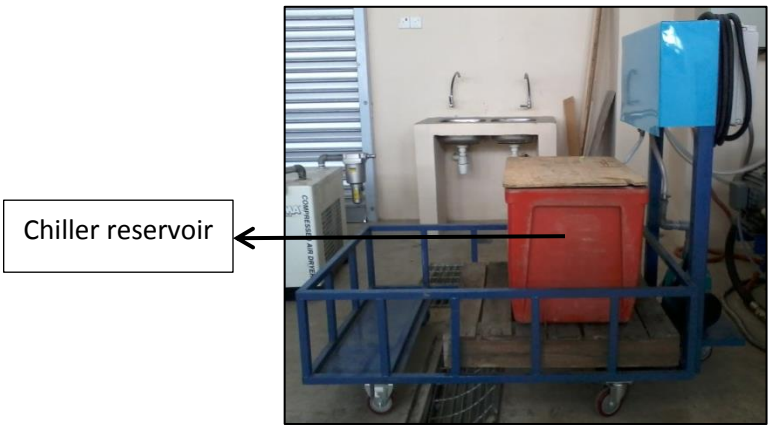

Figure 3.5 Chiller reservoir

3.4.3 Flow Rate of The Coolant

The flow rate of the coolant was controlled during the process of quenching the blank. The flow rate was set from 20, 30, and 40 L/min and the effect of flow rate was study on the formation on martensitic microstructure and specimen hardness.

Figure 3.6 Flow rate of the coolant

3.5 DESIGN OF EXPERIMENT

The statistical design used for this experiment was full factorial design whose design consists of 3 factors with 3 parameters which was pressed holding time, flow rate of the coolant, and temperature of the coolant. By using this 3^3 factorial, the effect of each parameter can be studied and also will reduce the costs of experimentation. Based on the average hardness value at each parameter level, analysis on its effect was performed. Analysis Of Variance (ANOVA) was then used to determine which process parameters were statistically significant. With ANOVA analysis, possible combination of optimum parameter can be predicted. The software that was used for the optimization was Design Expert.

Table 3.1 below shows the arrangement of each sample by the quenching parameters according to the full factorial design. The samples were named by the number and consonant. There were 27 specimens with the different arrangement of parameters.

Table 3.1 Full factorial design of experiment for hot press forming of 22MnB5 steel blank.

SAMPLE	QUENCHING TIME(S)	FLOW RATE(LPM)	COOLANT TEMPERATURE (^{0}C)
1B	3	20	27
2B	5	20	27
3B	7	20	27
1C	3	30	27
2C	5	30	27
3C	7	30	27
1D	3	40	27
2D	5	40	27
3D	7	40	27
1E	3	20	15
2E	5	20	15
3E	7	20	15
1F	3	30	15
2F	5	30	15
3F	7	30	15
1G	3	40	15
2G	5	40	15
3G	7	40	15
1H	3	20	5
2H	5	20	5
3H	7	20	5
1I	3	30	5
2I	5	30	5
3I	7	30	5
1J	3	40	5
2J	5	40	5
3J	7	40	5

3.6 SAMPLE PREPARATION

Before the testing processes were carried out, the blanks were prepared accordingly into the suitable shape and condition. The procedures for high carbon steel before running the testing process were as follow;

a) Sectioning process. The blank was cut into 10x10mm by using the cut off machine.
b) The sectioning part was then being mounted by using the hot mounted machine with the castable mounting media.
c) After the mounting process was completed, it's being grind to remove the scratch and smoothened the surface of the specimen by using the SiC grinding paper.

Table 3.2 Grinding procedure

Step	grit size	time (s)	wheel speed (rpm)	pressure (psi)
1	180	120	300	32
2	320	60	300	32
3	600	60	300	32

d) To provide an excellent surface of the specimen and eliminating smearing and pullout, it was run into the polishing process with a diamond compound and microid extender.

Table 3.3 Polishing procedure

Polishing type	time (s)	Wheel speed (rpm)	pressure (psi)
3 micron diamond compound/silk cloth/microid extender	240	250	30
1 micron diamond compound/red felt cloth/microid extender	120	250	30
Colloidal silica/imperial cloth/water	60	150	20

e) For the microscopic testing, the sample was etchants into 2% nital for 2 second after the polishing process.

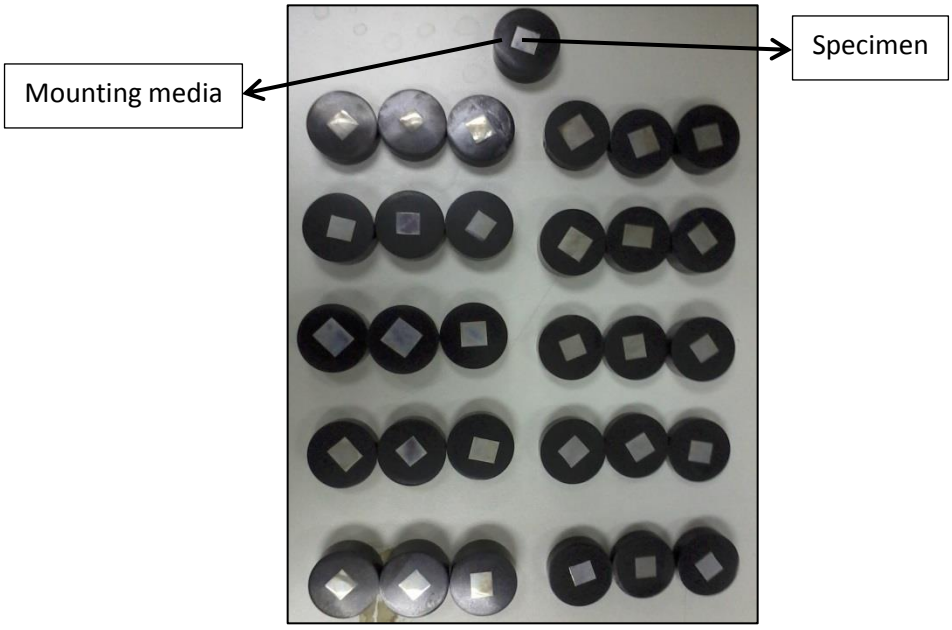

Figure 3.7 Specimen preparations for testing

3.7 MICROSCOPIC METALLURGY

Metallography was a technique used to reveal the internal structure of materials. In this hot stamping process, the microstructure of the blank after being quenched was analyzed using binocular metallurgical microscope [13]. The crystalline microstructure of boron alloyed steel was studied by examining it under a microscope at magnifications from 100 to 1000 times. The shape and size of the crystals indicates the composition and work hardening of boron alloyed steel. The first step was the recognition of the objective lenses and eyepieces used for the metallurgical microscope. After that, the blank was observed and at 100X-400X magnification. The grain structure was detected (ferrite, pearlite, austenite, martensite, bainite) and described the important features of the microstructure.

3.8 HARDNESS TEST

The Vickers hardness test was used to measure and determine the hardenability for boron alloyed steel. Hardness tests were performed on polished samples of boron, taken from the surface section of the blank, by using a programmable hardness test machine (Wilson Hardness Test) with uncertainty of about ±5 $HV_{0.5}$. This machine can scan the surface of the sample and measure hardness in each point. As a result of the indenter's shape, the impression on the surface of the specimen will be a square. The length of the diagonal of the square was measure through a microscope fitted with an ocular micrometer that contains movable knife-edges. The loads were between 1 and 1,000 g which referring to micro hardness test. The Vickers hardness values were calculated by the formula:

$$HV = \frac{2P\sin\left(\frac{\alpha}{2}\right)}{d^2} = 1.8544\left[\frac{P}{d^2}\right] \quad (3.1)$$

Where; P = the applied load (kg)

d = the diagonal length (mm).

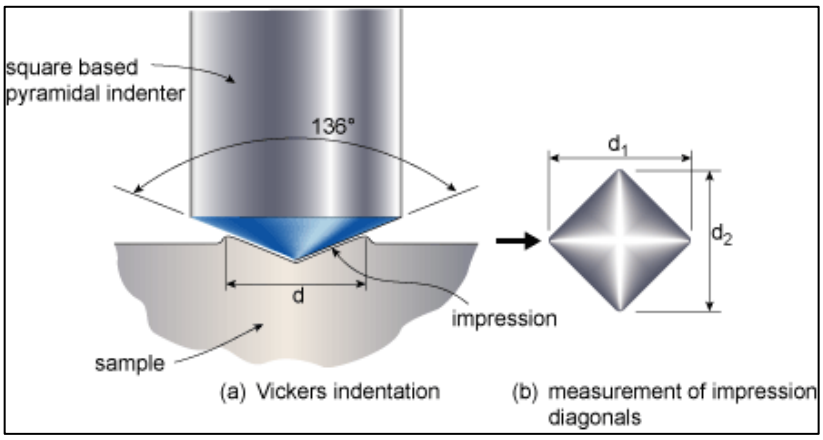

Figure 3.8 Vickers indentation and measurement of impression diagonals.

If indentation was placed too close to the edge of specimen, the work piece edge will bulge and the hardness number will decrease accordingly. To ensure an accurate test, the distance from the center of the indentation to the edge of the specimen must be at least two and one-half diameters. An indentation hardness test cold works the surrounding material. If another indentation was placed within this cold worked area, the reading usually will be higher than the real value. Generally, the softer the material, the more critical the spacing of indentions becomes. However, a distance three diameters from the center of one indentation to another was sufficient for most materials. Experimental steps of using Vickers hardness test were as follow;

a) The location of the indenter to be pressed was observed.
b) The load that was used was 500kPa.
c) The indenter was pressed into the sample by an accurately controlled test force.
d) The force was maintained for a specific dwell time of 10 second.
e) After the dwell time was complete, the indenter was removed leaved an indent in the sample that appears square shaped on the surface.
f) The size of the indent was determined optically by measuring the two diagonals of the square indent.

CHAPTER 4

RESULT AND DISCUSSION

4.1 INTRODUCTION

This chapter provides the result from the experiment of testing the material after being hot stamped. The result of hardness and microstructure of the specimen were analyzed using the statistical software to interpret the data.

4.2 BORON ALLOYED STEEL BLANK (22MnB5)

Figure 4.1 shows the grain structure of boron alloyed steel before the process of hot stamping and after it is being heated and quenched in the die. The grain structure of the as-received was the steel-rolled material composed of ferritic-pearlitic microstructure. Pearlite grain structures resemble human fingerprints as the picture in the figure above [18]. The ferrite microstructure was the white grain [18]. During the heating process, the shape of ferrite and pearlite were change as grains growing and collapsed each other. The quenching process makes the diffusion of carbon become restricted [18]. To make room for the carbon atoms, the lattice stretches along one crystal direction and the formation of martensite microstructure with a needle-like shape happened [18]. However, the ductility of the material was decreased because martensite formation makes the material become brittle. Beside the martensite microstructure, the bainite and retained austenite grain structure also appeared. The grain structure of bainite was darker than the martensite [17]. The formation of bainitic microstructure was due to the temperature drop of the specimen that was not fast enough. There was a retained

austenite microstructure appeared in the microstructure. This was because when soaking temperature was too high, there would be much more carbon and alloying element dissolved in the austenite and the austenite would become stable with decrease of martensite start temperature (Ms) [15]. As the result, more retained austenite can be remained in microstructure after quenched.

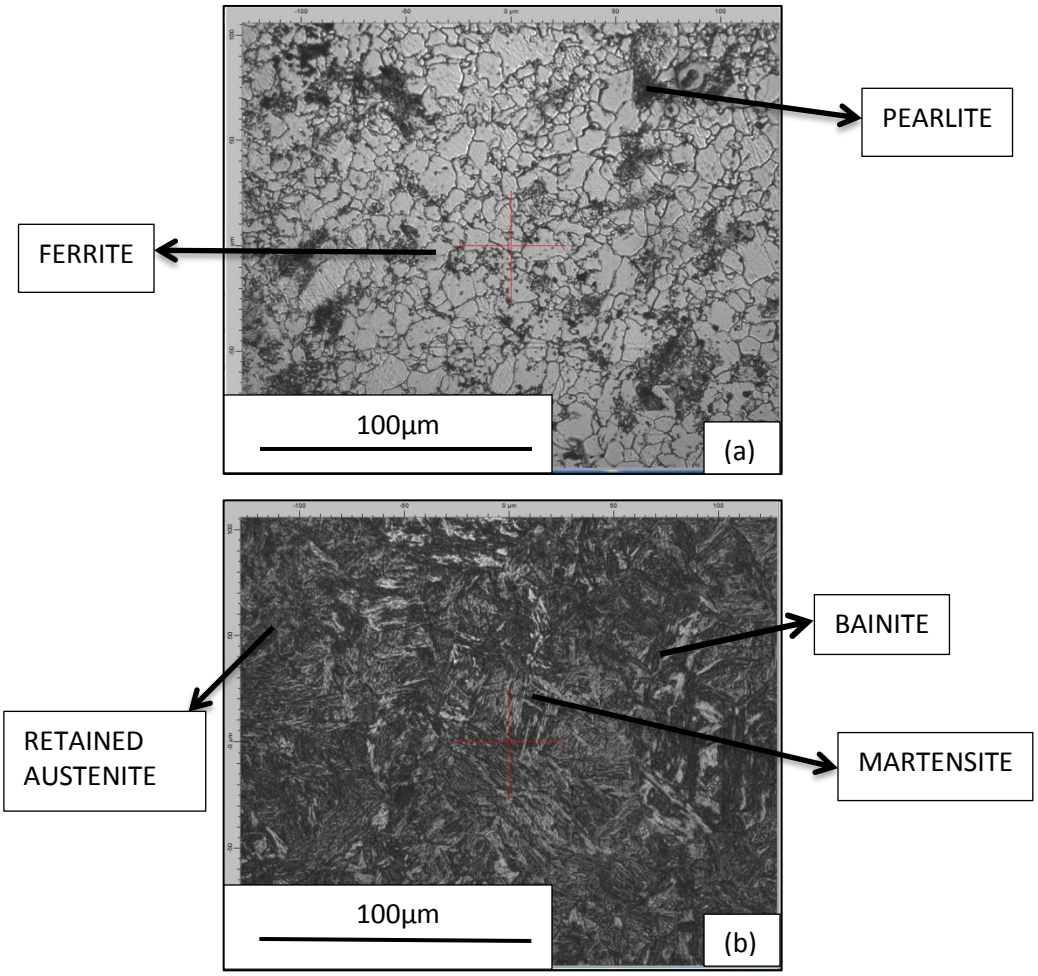

Figure 4.1 Microstructure of the specimen before (a) and after (b) being hot stamped.

4.3 HARDNESS PROPERTIES

Table 4.1 below shows the hardness value after the specimen being hot stamped. The hardness values were taken at 10 point for each specimen.

Table 4.1 The average hardness value for different sample

SAMPLE	QUENCHING TIME(S)	FLOW RATE(LPM)	COOLANT TEMPERATURE (^{O}C)	HARDNESS VALUE ($HV_{0.5}$)
1B	3	20	27	489.74
2B	5	20	27	540.1
3B	7	20	27	499.62
1C	3	30	27	516.58
2C	5	30	27	485.8
3C	7	30	27	543.3
1D	3	40	27	507.35
2D	5	40	27	487.17
3D	7	40	27	542.99
1E	3	20	15	492.69
2E	5	20	15	441.22
3E	7	20	15	511.96
1F	3	30	15	462.96
2F	5	30	15	482.05
3F	7	30	15	516.33
1G	3	40	15	502.23
2G	5	40	15	507.94
3G	7	40	15	536.82
1H	3	20	5	533.37
2H	5	20	5	524.71
3H	7	20	5	501.87
1I	3	30	5	509.64
2I	5	30	5	521.18
3I	7	30	5	447.55
1J	3	40	5	521.33
2J	5	40	5	534.88
3J	7	40	5	525.99

Figure 4.2 show the value of the hardness for every specimen of boron alloyed steel after being hot stamped. From the graph, the highest hardness value is 543.0 $HV_{0.5}$ which was being quenched at 7 second with a flow rate of 40 L/min and coolant temperature of 5^{o}C. From the hardness conversion chart, the highest tensile strength of the specimen is 1785.96 N/mm^{2}. The lowest hardness value is the 11th specimen that is being quenched at 5 second with a flow rate of 20L/min and coolant temperature of 15 ^{0}C. Compared to Karbasian research, to obtain the maximum martensitic content in the quenched sample the hardness value must be approximately 470 $HV_{0.5}$ [7].

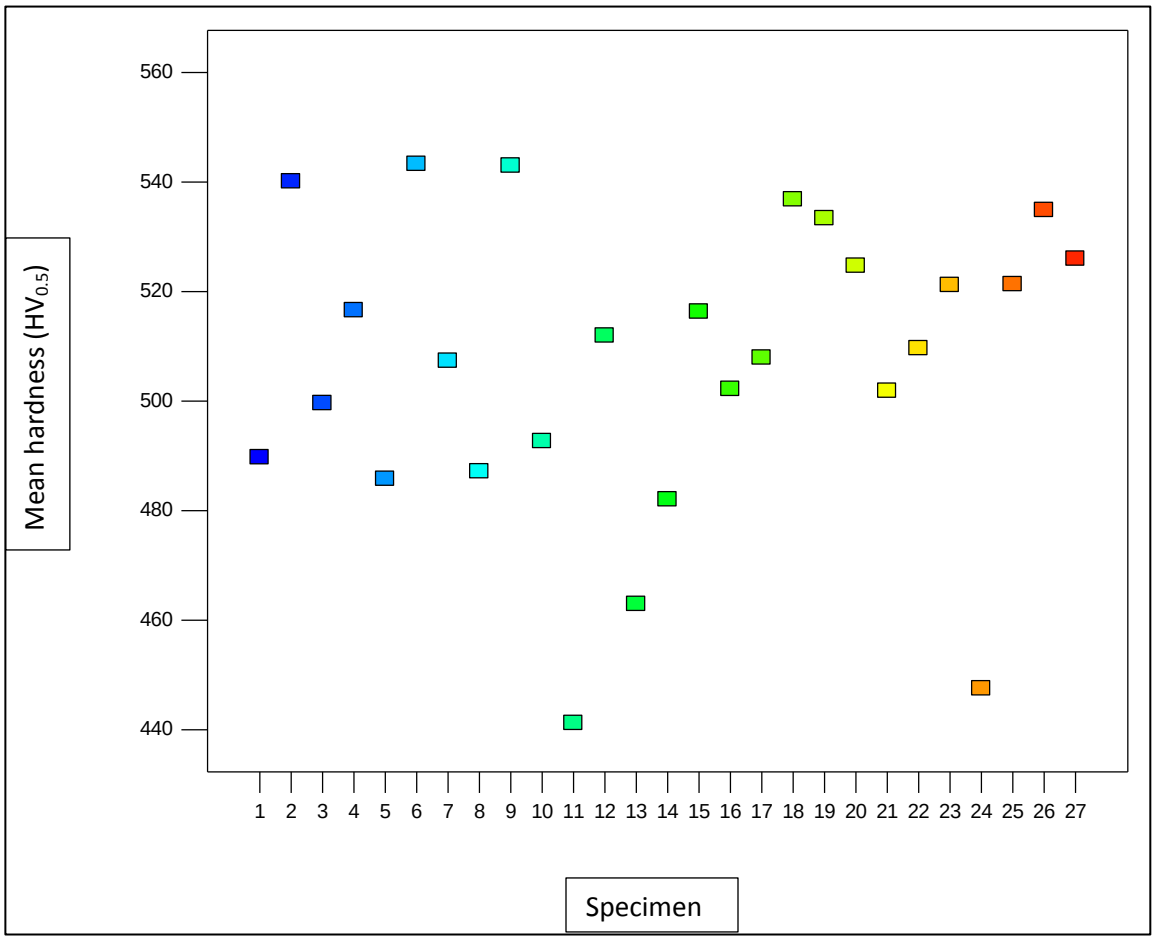

Figure 4.2 The average hardness ($HV_{0.5}$) of the specimen

4.3.1 Influence of Pressure Holding Time on Hardness Properties of Boron Alloyed Steel

The graph below shows the value of the hardness with the different quenching time. From Figure 4.3, 7 second seems the best quenching time to get the highest hardness value. The average hardness value for the 7 second of pressure holding time was 514.0 $HV_{0.5}$ compared to 3 and 5 seconds quenching time which is 504.0 $HV_{0.5}$ and 502.8 $HV_{0.5}$. The result shows that by increasing the press holding time will increase the hardness value of the specimen. This was because by increasing the press holding time will increase the heat transfer from the blank to the die and thus will faster the martensite start temperature (Ms). Increasing the heat transfer by conduction between the die and blank during the process of quenching also will increase the cooling rate of the specimen. Compared to the Chengxi et al. researched, by increasing the pressure holding time will faster the temperature drop and in order to obtain a good cooling effect, the pressure holding time should exceed 8 second [14].

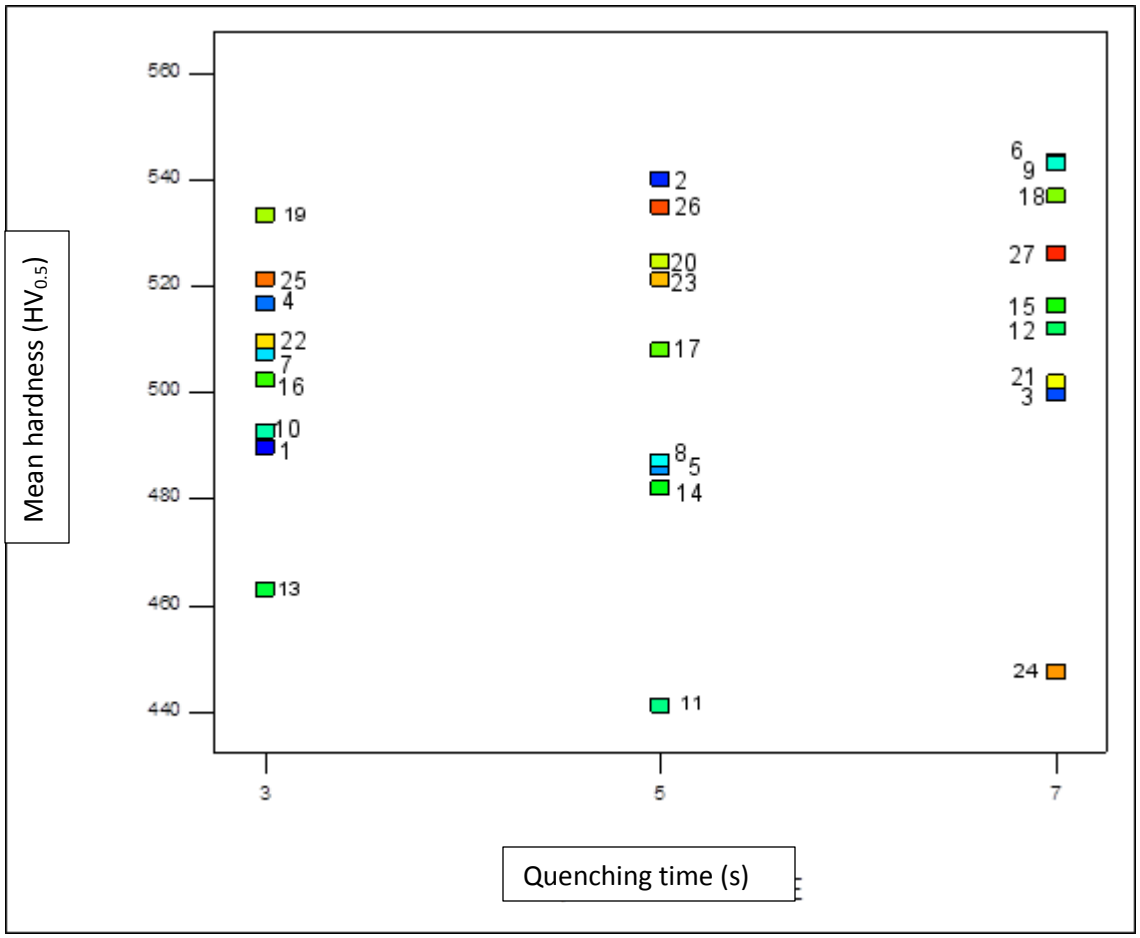

Figure 4.3 Quenching time (s) VS hardness test ($HV_{0.5}$)

4.3.2 Influence of Flow Rate of Chiller Reservoir on Hardness Properties of Boron Alloyed Steel

Figure 4.4 shows the hardness value of the specimen at a different flow rate. The result shows that the average highest hardness value can be achieved by using the flow rate of 40 L/min which was 518.5 $HV_{0.5}$ compared to the flow rate of 20 L/min and 30 L/min which is just 503.9 $HV_{0.5}$ and 498.4 $HV_{0.5}$. The hardness of the specimen increase once the coolant flow rate of the process was raised. The function of the flow rate was to transfer the heat that was conducted by the die from the blank during the press process. Increasing the flow rate increased the heat flow of the coolant. That was because the

flow of the water became fully turbulent in the pipes with the increasing the cooling water rate. The heats of the die were taken away by the cooling water because the heat conduct was more sufficient between the cooling water and dies. Chengxi et al. research shows that with the increasing the water velocity, the temperature of the die will reduced and from the numerical analysis, the temperature of the punching die decrease from 152.6 ^{0}C (1.5m/s) to 137.3 ^{0}C (m/s) [14].

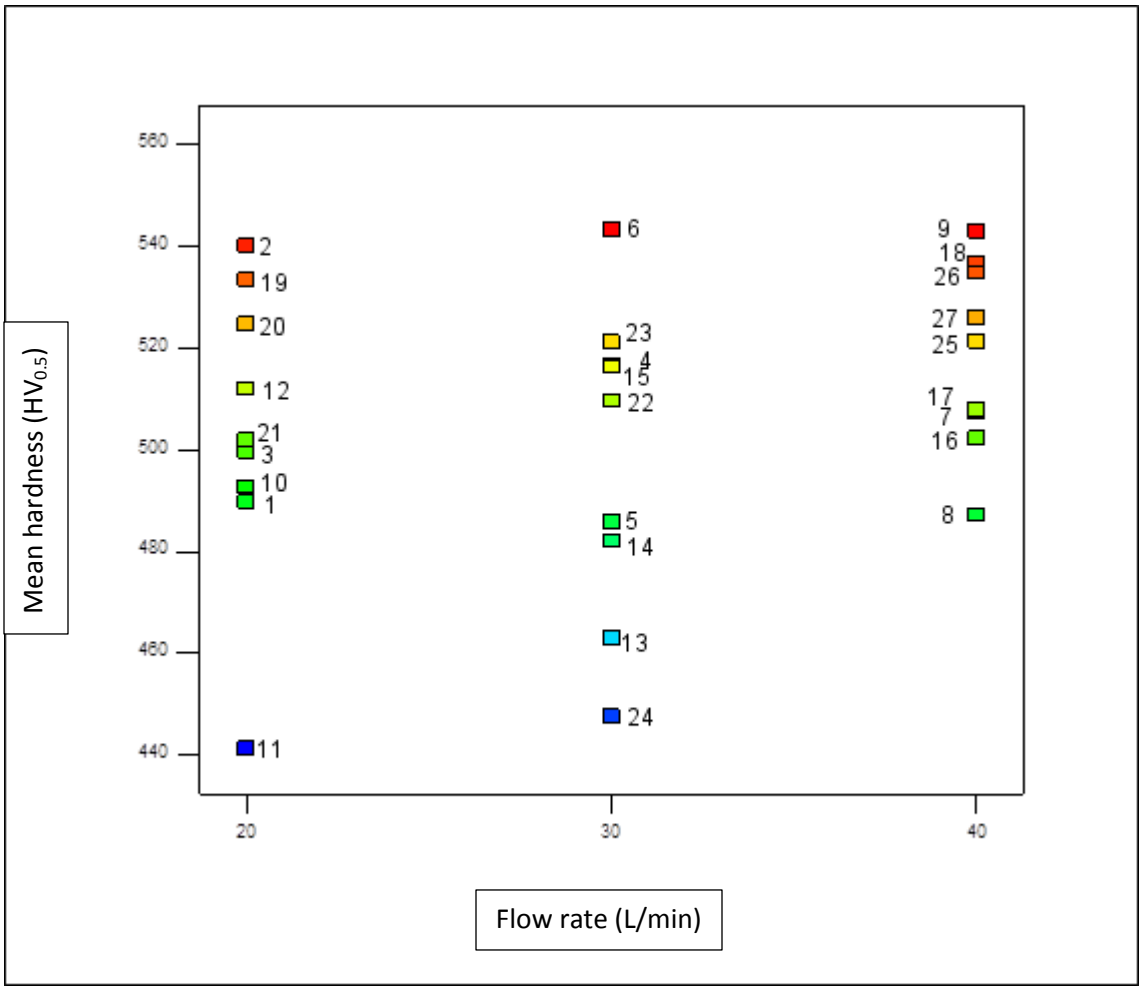

Figure 4.4 Flow rate (L/min) VS hardness value ($HV_{0.5}$)

4.3.3 Influence of The Temperature of The Coolant During Quenching on Hardness Properties of Boron Alloyed Steel

Figure 4.5 show the hardness value of the boron alloyed steel with the different temperature of the coolant. At 27 ^{0}C of the coolant temperature, the highest average hardness achieved, which was 513.4 $HV_{0.5}$ compared to the 5 ^{0}C and 15 ^{0}C of coolant temperature which was 507.0 $HV_{0.5}$ and 494.9 $HV_{0.5}$. Referring to the continuous-cooling transformation diagram, lowering the cooling temperature will diffuse out the carbon's atom and will result into the transformation of pearlitic microstructure.

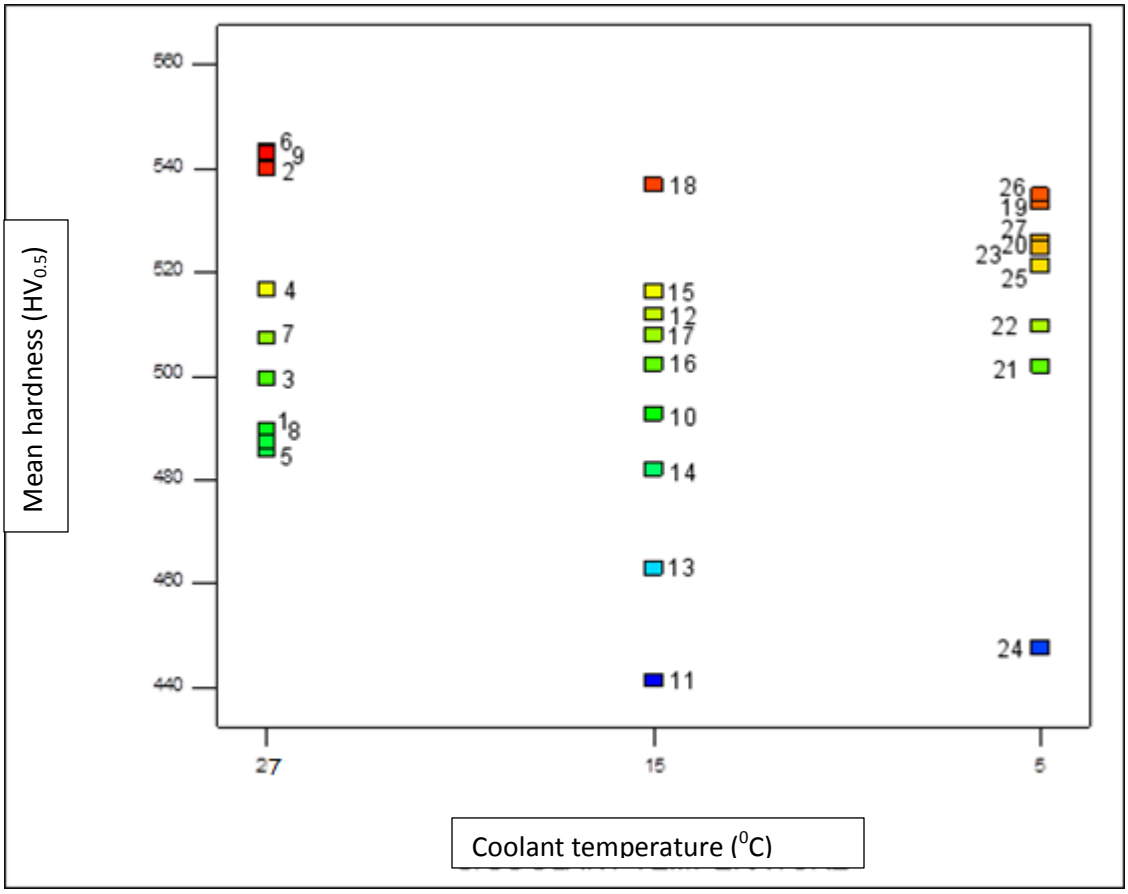

Figure 4.5 Temperature of the coolant (^{0}C) VS hardness value ($HV_{0.5}$)

4.4 MICROSCOPY

Figure 4.6 shows the comparison between flow rate of the coolant and the quenching time with the constant coolant temperature which is 27 ^{0}C. As the quenching time and the flow rate increase, the traces of martensite microstructure increase. The grain structure of the specimen looks finer at the flow rate of 40 L/min compared to 20 L/min and 30 L/min. This was because by increasing the press-holding time and the flow rate, the cooling rate were also increased. Due to the fast cooling, the diffusion of carbon atom was more restricted [18]. To make room for the carbon atom, the lattice structure stretched along one crystal direction and the formation of the needle-shape martensite happened [18]. The study of effect of quenching rate on microstructure both the flat-die hot-stamped and water-quenched specimens contains fully lath-martensite, but the hot-stamped specimen also contains a few large grains [20].

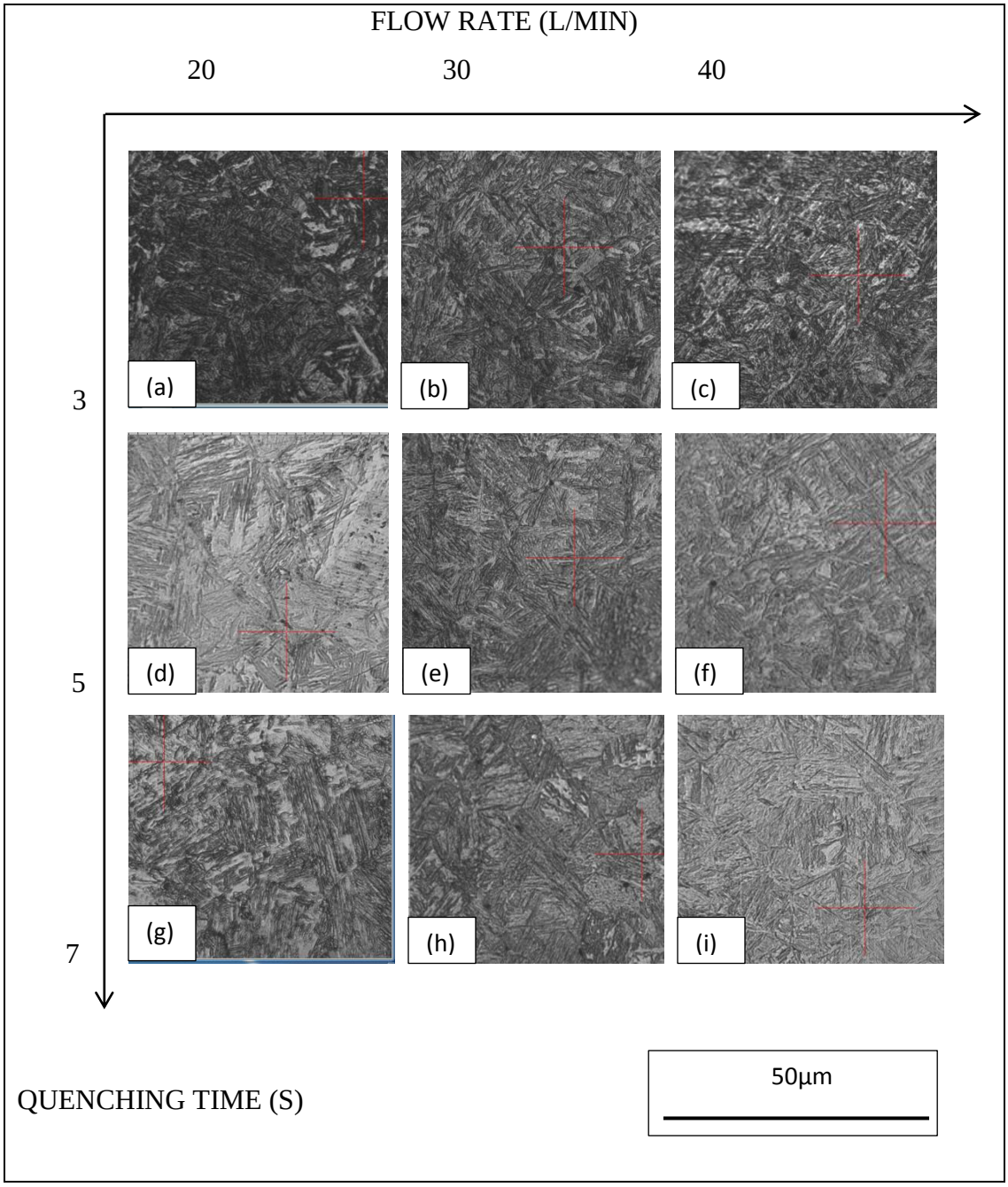

Figure 4.6 Micrograph of martensite structure produced at different flow rate and quenching time of (a), (b), and (c) 3 second, (d), (e), and (f) 5 second, and (g), (h), and (i) 7 second.

From the Figure 4.7, as the coolant temperature decrease, the formation of martensitic microstructure decreases and the formation of bainitic microstructure increases. The microstructure of bainite seems quite similar with the martensite. But the grain structure of the bainite appear darker then martensite due to low reflectivity [17]. The formation of bainitic microstructure was due to the temperature drop of the specimen that was not fast enough. After 3 s of holding time at temperature of 375 ^{0}C, bainite transformation has not started and a fully martensitic microstructure was obtained by quenching [17].

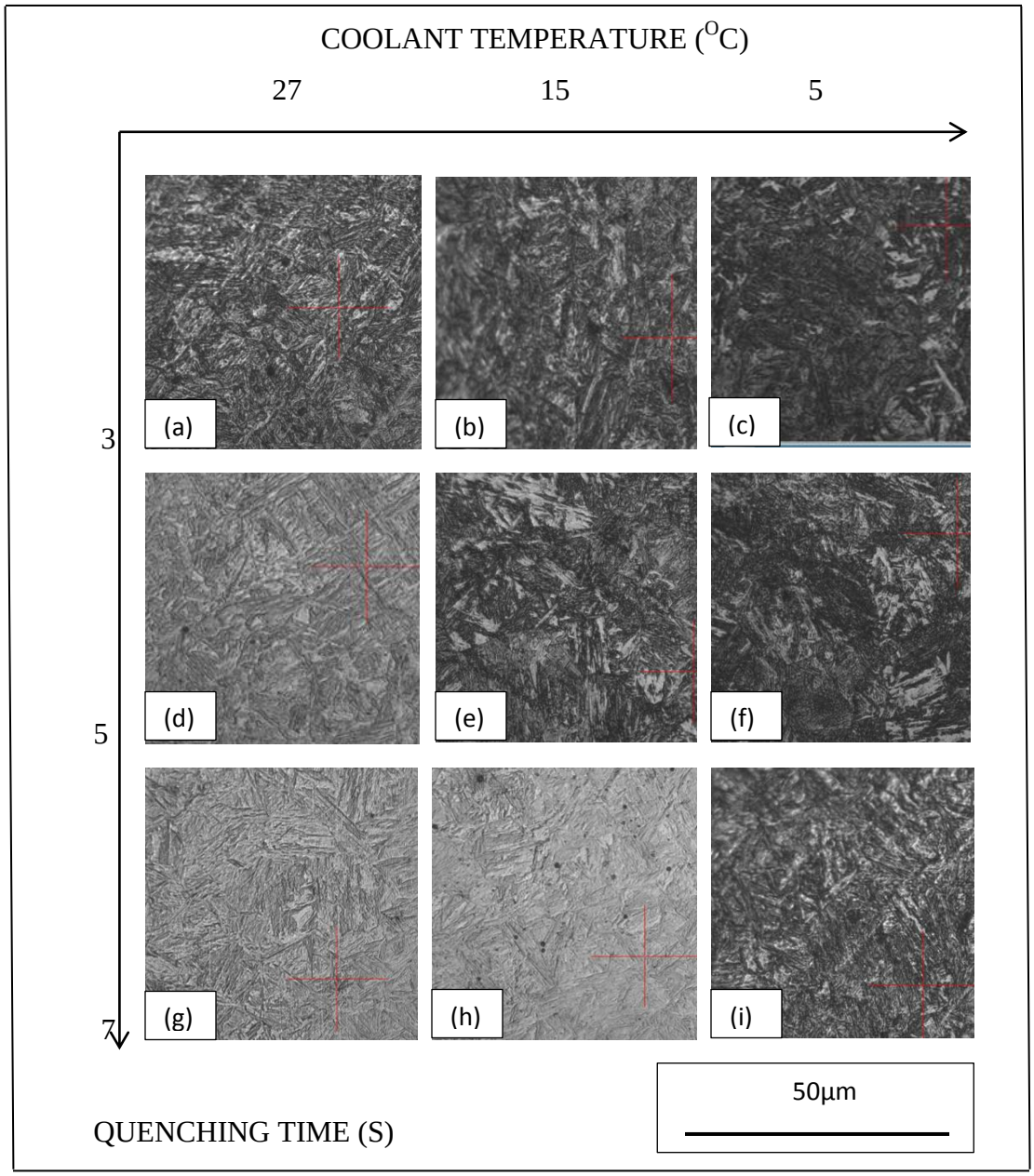

Figure 4.7 Micrograph of martensite structure produced at different quenching time and coolant temperature of (a), (d), and (g) 27 ^{0}C, (b), (e), and (h) 15 ^{0}C, and (c), (f), and (i) 5 ^{0}C.

Figure 4.8 above shows the microstructure of the material at different coolant temperature and flow rate with a constant quenching time which was 7 second. There was a retained austenite pearlite microstructure appeared in the microstructure. This is because of the existence of chemical elements segregation, the distribution of alloy elements in the austenite is uneven [17]. So the austenite can be partially transformed into the pearlite during the cooling and the other austenite remains unchanged and retained to the room temperature. The figure also shows that at flow rate of 40 L/min and coolant temperature of 27 ^{0}C produced the finest grain structure.

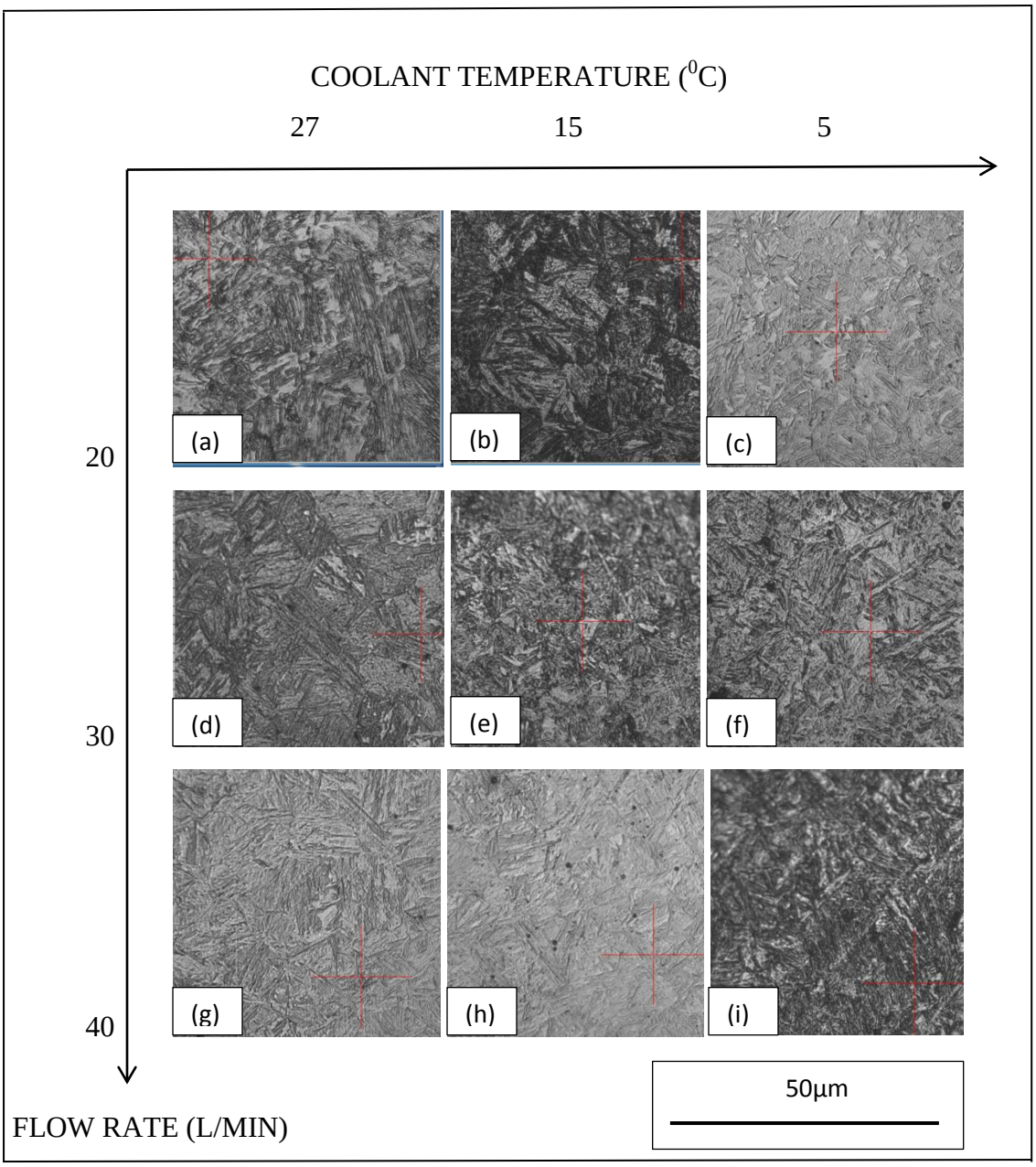

Figure 4.8 Micrograph of martensite structure produced at different coolant temperature and flow rate of (a), (b), and (c) 20 L/min, (d), (e), and (f) 30L/min, and (g), (h), and (i) 40L/min.

4.5 STATISTICAL ANALYSIS

4.5.1 Analysis of Variance

After running an analysis, there was one parameter that doesn't significant with the model which was the temperature of the coolant. By reducing the coolant temperature, the responses become significant. Table 4.2 shows the ANOVA for response surface reduced quadratic model. The Model F-value of 2.73 implies the model is significant. There is only a 3.13% chance that a "Model F-Value" this large could occur due to noise.

Table 4.2 Analysis of variance table [Partial sum of squares - Type III]

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	9677.02	7	1382.43	2.73	0.0313	significant
A-qunching time	527.71	1	527.71	1.04	0.3179	
B-flow rate	959.51	1	959.51	1.89	0.1817	
AB	497.17	1	497.17	0.98	0.3320	
AC	1975.14	1	1975.14	3.89	0.0601	
A^2	281.13	1	281.13	0.55	0.4638	
B^2	1186.56	1	1186.56	2.34	0.1392	
C^2	2337.74	1	2337.74	4.61	0.0421	
Residual	12171.16	24	507.13			
Lack of Fit	12171.16	19	640.59			
Pure Error	0.000	5	0.000			
Cor Total	21848.18	31				

4.5.2 Numerical Optimization

Table 4.3 shows the required model that needed to obtain an optimization analysis. The value of the mean hardness and coolant temperature was set to be maximizing while the quenching time and flow rate were set in range in order to achieve an objective which is optimum cooling rate besides enhance the tool life and reduced cycle-time as well. There were 17 solutions for the optimization that approached the desirability of 1.

Table 4.3 Optimization analysis

Name	Goal	Lower limit	Upper limit	Lower weight	Upper weight	Importance
Quenching time (s)	Is in range	3	7	1	1	3
Flow rate (L/min)	Is in range	20	40	1	1	3
Coolant temperature (^{0}C)	maximize	5	27	1	1	5
Mean hardness ($HV_{0.5}$)	maximize	441.22	543.3	1	1	3

From Table 4.4, the best optimization solution was being quenched at 7 second with the flow rate of 40L/min and the coolant temperature of 27 ^{0}C that will produced the maximum value of hardness which is 551.3 HV0.5.

Table 4.4 Solution for optimization

NUMBER	QUENCHING TIME (s)	FLOW RATE (L/min)	COOLANT TEMPERATURE (^{0}C)	MEAN HARDNESS ($HV_{0.5}$)	DESIRABILITY
1	7.00	40.00	27.00	551.3	1.000
2	6.99	37.90	27.00	543.5	1.000
3	6.84	39.23	27.00	545.5	1.000
4	6.68	39.89	27.00	545.1	1.000
5	6.65	39.65	27.00	543.7	1.000
6	6.95	39.19	27.00	547.2	1.000
7	6.88	39.41	27.00	546.9	1.000
8	6.79	39.95	27.00	547.3	1.000
9	6.93	39.55	27.00	548.2	1.000
10	6.98	38.40	27.00	544.9	1.000
11	6.69	39.45	27.00	543.6	1.000
12	6.70	39.89	27.00	545.5	1.000
13	6.77	39.88	27.00	546.5	1.000
14	6.98	39.99	27.00	550.9	1.000
15	6.68	39.65	27.00	544.2	1.000
16	6.69	39.56	27.00	544.1	1.000
17	6.87	38.80	27.00	544.5	1.000

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 INTRODUCTION

In this chapter, the investigations on hot stamping process of boron alloyed steel were summarized with the objective to optimize the quenching process. The effects of the quenching parameters on the martensitic transformation and hardness properties during a hot press forming process which as planed very similar to the hot stamping process schedules were studied.

5.2 CONCLUSION

The press holding time and flow rate of the water coolant were affecting the hardness properties of the boron alloyed steel. It can be concluded that to achieve the highest hardness value up to 551.3 $HV_{0.5}$, the specimen should be quenched at 7 second with the flow rate of 40 L/min and coolant temperature of 27 ^{0}C. The martensite content also was increased as the hardness value increased but it is impossible to achieve a fully martensitic microstructure after the specimen being hot stamped. One of the main functions of hot stamping process was to extract heat from the blank. The die must be able to achieve a minimum cooling rate of 30 ^{0}C/s to achieve the highest martensite transformation.

5.3 RECOMMENDATION FOR THE FUTURE RESERCH

Besides controlling the quenching parameter during the stamping process, optimizing locations of cooling channels in hot stamping dies and cooling system design also will affect the optimization process. Optimization of the cooling system in hot stamping tools will greatly reduce the cycle time, because cooling the part after the dies are closed is critical to achieve the desired cooling rate. Selecting the die material also necessary to make good heat conductivity between the die and blank.

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APPENDICES

State	Hardness	Method	Conv. Hard	Rel. Posi	DiagX	DiagY
MEASURED	483.3	HV0,5	459 HBW	0.000 mm	0.0442	0.0434
MEASURED	499.9	HV0,5	475 HBW	0.000 mm	0.0436	0.0425
MEASURED	483.3	HV0,5	459 HBW	0.000 mm	0.0448	0.0428
MEASURED	446.7	HV0,5	425 HBW	0.000 mm	0.045	0.0461
MEASURED	455.3	HV0,5	433 HBW	0.000 mm	0.0459	0.0443
MEASURED	506.9	HV0,5	482 HBW	0.000 mm	0.043	0.0425
MEASURED	500.1	HV0,5	475 HBW	0.000 mm	0.0424	0.0437
MEASURED	503.4	HV0,5	478 HBW	0.000 mm	0.043	0.0428
MEASURED	510.3	HV0,5	485 HBW	0.000 mm	0.0427	0.0425
MEASURED	500.1	HV0,5	475 HBW	0.000 mm	0.043	0.0431

1B

State	Hardness	Method	Conv. Hard	Rel. Posi	DiagX	DiagY
MEASURED	575.9	HV0,5	547 HBW	0.000 mm	0.0395	0.0408
MEASURED	503.4	HV0,5	478 HBW	0.000 mm	0.0427	0.0431
MEASURED	535.9	HV0,5	509 HBW	0.000 mm	0.0415	0.0417
MEASURED	567.5	HV0,5	540 HBW	0.000 mm	0.0409	0.0399
MEASURED	528.5	HV0,5	503 HBW	0.000 mm	0.0418	0.042
MEASURED	543.6	HV0,5	517 HBW	0.000 mm	0.0406	0.042
MEASURED	536	HV0,5	509 HBW	0.000 mm	0.0418	0.0414

2B

State	Hardness	Method	Conv. Hard	Rel. Posi	DiagX	DiagY
MEASURED	510.4	HV0,5	485 HBW	0.000 mm	0.043	0.0423
MEASURED	521	HV0,5	495 HBW	0.000 mm	0.0427	0.0417
MEASURED	521.1	HV0,5	495 HBW	0.000 mm	0.0415	0.0428
MEASURED	539.8	HV0,5	513 HBW	0.000 mm	0.0415	0.0414
MEASURED	517.6	HV0,5	492 HBW	0.000 mm	0.0415	0.0431
MEASURED	503.4	HV0,5	478 HBW	0.000 mm	0.0427	0.0431
MEASURED	503.3	HV0,5	478 HBW	0.000 mm	0.0433	0.0425
MEASURED	503.3	HV0,5	478 HBW	0.000 mm	0.0433	0.0425
MEASURED	517.5	HV0,5	491 HBW	0.000 mm	0.0421	0.0425
MEASURED	528.4	HV0,5	502 HBW	0.000 mm	0.0421	0.0417

1C

State	Hardness	Method	Conv. Hard	Rel. Posi	DiagX	DiagY
MEASURED	506.9	HV0,5	482 HBW	0.000 mm	0.043	0.0425
MEASURED	486.6	HV0,5	463 HBW	0.000 mm	0.0433	0.044
MEASURED	493.2	HV0,5	469 HBW	0.000 mm	0.0433	0.0434
MEASURED	470.6	HV0,5	448 HBW	0.000 mm	0.045	0.0437
MEASURED	473.7	HV0,5	451 HBW	0.000 mm	0.0439	0.0446
DIAGERR	483.4	HV0,5	459 HBW	0.000 mm	0.0427	0.0449
MEASURED	473.7	HV0,5	451 HBW	0.000 mm	0.0439	0.0446
MEASURED	480.1	HV0,5	456 HBW	0.000 mm	0.0439	0.044
MEASURED	496.6	HV0,5	472 HBW	0.000 mm	0.0433	0.0431
MEASURED	493.2	HV0,5	469 HBW	0.000 mm	0.0439	0.0428

2C

State	Hardness	Method	Conv. Hard	Rel. Posi	DiagX	DiagY
MEASURED	555.5	HV0,5	528 HBW	0.000 mm	0.0412	0.0405
MEASURED	584.4	HV0,5	555 HBW	0.000 mm	0.0401	0.0396
MEASURED	551.4	HV0,5	524 HBW	0.000 mm	0.0409	0.0411
MEASURED	535.9	HV0,5	509 HBW	0.000 mm	0.0421	0.0411
MEASURED	559.5	HV0,5	531 HBW	0.000 mm	0.0409	0.0405
MEASURED	521.1	HV0,5	495 HBW	0.000 mm	0.043	0.0414
MEASURED	539.8	HV0,5	513 HBW	0.000 mm	0.0412	0.0417
MEASURED	524.7	HV0,5	499 HBW	0.000 mm	0.0424	0.0417
MEASURED	528.5	HV0,5	503 HBW	0.000 mm	0.0418	0.042
MEASURED	532.2	HV0,5	506 HBW	0.000 mm	0.0418	0.0417

3C

State	Hardness	Method	Conv. Hard	Rel. Posi	DiagX	DiagY
MEASURED	521.1	HV0,5	495 HBW	0.000 mm	0.043	0.0414
MEASURED	500.1	HV0,5	475 HBW	0.000 mm	0.0424	0.0437
MEASURED	528.5	HV0,5	503 HBW	0.000 mm	0.0418	0.042
MEASURED	499.9	HV0,5	475 HBW	0.000 mm	0.0433	0.0428
MEASURED	506.9	HV0,5	482 HBW	0.000 mm	0.043	0.0425
MEASURED	496.6	HV0,5	472 HBW	0.000 mm	0.0433	0.0431
DIAGERR	506.7	HV0,5	482 HBW	0.000 mm	0.0439	0.0417
MEASURED	506.9	HV0,5	482 HBW	0.000 mm	0.0427	0.0428
MEASURED	503.4	HV0,5	478 HBW	0.000 mm	0.043	0.0428
MEASURED	503.4	HV0,5	478 HBW	0.000 mm	0.0427	0.0431

1D

State	Hardness	Method	Conv. Hard	Rel. Posi	DiagX	DiagY
DIAGERR	499.9	HV0,5	475 HBW	0.000 mm	0.045	0.0411
DIAGERR	499.9	HV0,5	475 HBW	0.000 mm	0.045	0.0411
MEASURED	477	HV0,5	453 HBW	0.000 mm	0.045	0.0431
MEASURED	455.4	HV0,5	433 HBW	0.000 mm	0.0462	0.044
DIAGERR	489.9	HV0,5	466 HBW	0.000 mm	0.045	0.042
MEASURED	483.3	HV0,5	459 HBW	0.000 mm	0.0439	0.0437
MEASURED	486.6	HV0,5	463 HBW	0.000 mm	0.0436	0.0437
MEASURED	486.6	HV0,5	463 HBW	0.000 mm	0.0436	0.0437
MEASURED	496.5	HV0,5	471 HBW	0.000 mm	0.0439	0.0425
MEASURED	496.6	HV0,5	472 HBW	0.000 mm	0.0436	0.0428

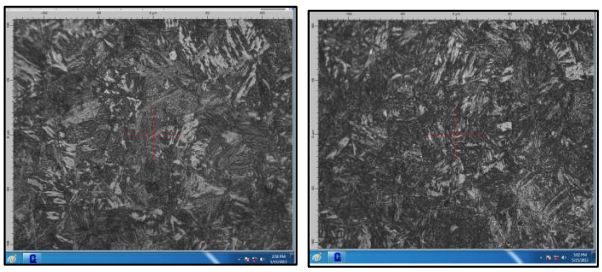
2D

State	Hardness	Method	Conv. Hard	Rel. Posi	DiagX	DiagY
MEASURED	524.7	HV0,5	499 HBW	0.000 mm	0.043	0.0411
MEASURED	547.4	HV0,5	520 HBW	0.000 mm	0.0421	0.0402
DIAGERR	532.2	HV0,5	506 HBW	0.000 mm	0.043	0.0405
MEASURED	539.7	HV0,5	513 HBW	0.000 mm	0.0421	0.0408
MEASURED	539.8	HV0,5	513 HBW	0.000 mm	0.0412	0.0417
MEASURED	539.8	HV0,5	513 HBW	0.000 mm	0.0412	0.0417
MEASURED	551.4	HV0,5	524 HBW	0.000 mm	0.0406	0.0414
MEASURED	532.1	HV0,5	506 HBW	0.000 mm	0.0427	0.0408
MEASURED	559.3	HV0,5	531 HBW	0.000 mm	0.0406	0.0408
MEASURED	563.5	HV0,5	535 HBW	0.000 mm	0.0412	0.0399

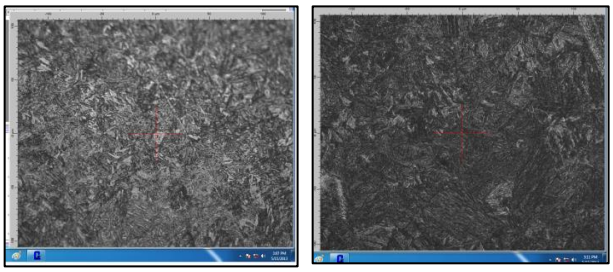
3D

State	Hardness	Method	Conv. Hard	Rel. Posi	DiagX	DiagY
MEASURED	483.4	HV0,5	459 HBW	0.000 mm	0.0436	0.044
MEASURED	480.1	HV0,5	456 HBW	0.000 mm	0.0439	0.044
MEASURED	532.1	HV0,5	506 HBW	0.000 mm	0.0427	0.0408
MEASURED	483.3	HV0,5	459 HBW	0.000 mm	0.0442	0.0434
MEASURED	500.1	HV0,5	475 HBW	0.000 mm	0.0424	0.0437
MEASURED	521	HV0,5	495 HBW	0.000 mm	0.0427	0.0417
MEASURED	486.6	HV0,5	463 HBW	0.000 mm	0.0427	0.0446
MEASURED	480.1	HV0,5	456 HBW	0.000 mm	0.0439	0.044
MEASURED	480.1	HV0,5	456 HBW	0.000 mm	0.0439	0.044
MEASURED	480.1	HV0,5	456 HBW	0.000 mm	0.0439	0.044

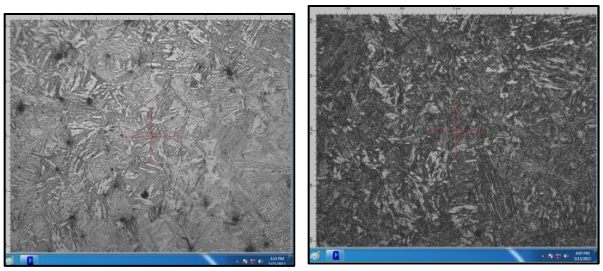
1E



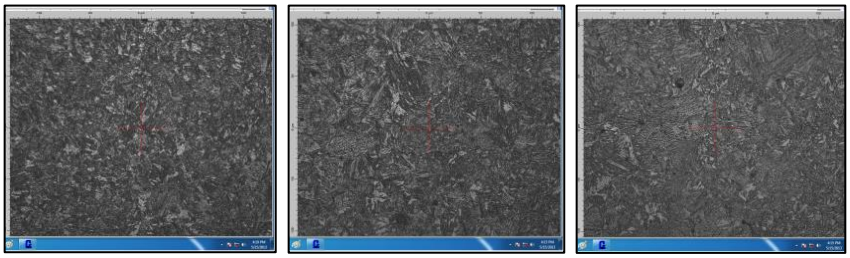
1E AND 2E



1F AND 2F



3F AND 1H



2H, 1I AND 2I