THE EFFECT OF DEEP CRYOGENIC ON TENSILE STRENGTH AND IMPACT TOUGHNESS IN QUENCH TEMPERED STEEL PLATE AS A CANDIDATE FOR BALLISTIC RESISTANCE MATERIAL

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Ballistic resistant materials are materials containing right combination of hardness, strength, and toughness. The quench process produces high hardness and tensile strength but decreases toughness. The hardening process has been performed using an induction machine and a tempering process on a medium carbon steel plate. This work aimed to determine and analyze the effect of deep cryogenic treatment (DCT) on steel plates that have been quenched tempered. This research utilized steel plates of 130 x 130 x 8 mm size which has been quenched and then immersed in liquid nitrogen at a temperature of -196°C for 1, 5, 10, and 20 days. The micro Vickers hardness test specimen, tensile test and charpy impact test were made to determine the effect of immersion time. The test results and analysis showed that DCT had the ability to change microstructure, improve the hardness, tensile strength, and impact toughness. Furthermore, the maximum hardness was obtained during the immersion treatment of 20 days, which was 449.45 VHN and 1107.53 MPa, respectively. However, the highest toughness was obtained during the immersion of 10 days, which was 1,001 J/mm^2. In order to get the optimal combination of ballistic characters, further ballistic testing is needed, both in simulation using the finite element method and ballistic experiment test.

KEYWORDS

medium carbon steel, quench temper, cryogenic, ballistic resistance

INTRODUCTION

Ballistic resistant vehicles are one of the components of the national defense and security system. Ballistic resistant vehicles are designed and built to attack and protect the vehicle crew. In this case, steel is still used as the main material in military vehicles. Since it has a high density, it affects the increase in fuel consumption, range, reliability and speed of military vehicles [Piers et al. 2006] as well as agility in the terrain traversed [Kim et al. 1998]. In addition to having a protective function, steel is still used as a military vehicle material because it also has a construction function on the vehicle. Metal is the most common material used as armor material due to its cost-effectiveness, strength, and ease of manufacture [Bekci et al. 2021]. And to increase hardness, strength and toughness, it is carried out with a quench temper heat treatment process so that the ballistic resistance increases.

Ballistic resistant materials or armor are made to resist projectile with very high velocities. Armor is made to resist projectile penetration by breaking the projectile and absorb the impact. The ballistic resistance of steel is a complex function of the steel mechanical properties, such as hardness, crushed strength, tensile strength, ductility, and impact toughness. One of those properties alone cannot be used to predict ballistic resistance. Therefore, the optimal combination of hardness, strength, and toughness is an important factor in increasing ballistic resistance [Jena et al. 2010a]. When the hardness is increased, it does not directly increase the ballistic resistance. Hardness above 450 HB will increase the susceptibility to the formation of adiabatic share band (ASB) [Ryan et al. 2016]. ASB is associated with ultra-high velocity collisions. Most of the armor is still susceptible to the formation of ASB formations which then cause cracks, which further causes serious damage to the ballistic performance [Jo et al. 2020]. The damage in ballistic-resistant plates is also affected by bullet caliber, projectile material, muzzle velocity, and shooting range [Riyono et al. 2019]. A projectile with the same velocity but different mass and material results in a different crater shape in the target plates. Besides, the angle of attack affects the ballistic resistance; the ballistic resistance increases as the impact angle increases [Bekci et al. 2021].

High-strength bainitic steels have attracted many people these days due to their excellent combination of strength, tenacity, toughness, and high ballistic mass efficiency. [Jo et al. 2020] improved the ballistic performance using a method with a transformation-induced plasticity mechanism. It is done by controlling the time of austempering in various volume fractions and the stability of retained austenite by maintaining the high hardness. The result of the study showed that the transformation-induced plasticity mechanism achieved from a large quantity of metastable retained austenite significantly increased the ballistic performance in the high-strength bainitic steels.

The quench process on medium carbon steel has the ability to improve the hardness and ballistic resistance. The higher the hardness value, the more increase the ballistic resistance, so that at a certain hardness value, the ballistic resistance will decrease due to a failure process caused by shifting and cracking to holes due to ballistic impact [Dikshit et al. 1995]. High hardness can decrease toughness. Toughness is an important factor in increasing ballistic resistance [Jena et al. 2010a]. Therefore, the tempering process is performed to further increase its ballistic resistance [Jena et al. 2010b].

[Purwanto et al. 2020a; Purwanto et al. 2020b; Purwanto et al. 2019; Purwanto et al. 2021a; Purwanto et al. 2021b] have performed a quench process, followed by a tempering process on a commercial medium carbon steel plate as a candidate for ballistic resistant material. Simulation using the finite element method also proves that the quench tempering process improved ballistic resistant materials. The highest tensile strength, hardness, and toughness were obtained at an austenite temperature of 900°C austenite and quench in various oil media on commercial S45C steel samples [Purwanto et al. 2021a]. The simulation results using finite element method and oil media produces the lowest residual velocity compared to being quench in water media [Purwanto et al. 2020a]. The toughness of quench steel can be increased optimally at a tempering temperature of 300°C, but the ballistic resistance simulation shows that tempering temperature of 100°C produces the most optimal ballistic resistance [Purwanto, et al. 2020b; Purwanto et al. 2021b]. The surface hardening process on the plate is able to increase ballistic resistance by using 7.62 mm projectiles. With surface hardening, the plate surface becomes stronger and that case hardening increased the perforation resistance by more than 20% compared to no treatment [Holmen et al. 2017].

Another previous research project reported that cryogenic treatment and deep cryogenic treatment (DCT) can increase the strength of metallic materials. Cryogenic and DCT are treatments in the forms of providing cold and or super cold temperatures for a certain period of time. Cryogenic treatment usually utilizes liquid nitrogen at a temperature of -196°C after the quenching and tempering process. Tests have been performed at low temperatures on aluminum material obtaining that the rate of impact damage to the main wall at cryogenic temperatures is reduced compared to treatment at room temperature [Ohtani et al. 2006]. Research on cryogenic treatment is mainly focused on the conversion of retained austenite to martensite and the deposition of fine secondary carbides. Stainless steel immersed in liquid helium exhibits ductile behavior and high strength as a result of tensile testing [Czarkowski et al. 2014]. Cryogenic treatment of Fe-Mn-C alloy improved grain, increased elongation, yield strength, and as well as significantly increased ultimate tensile strength [Koyama et al. 2013]. It was also reported that DCT which is part of the heat treatment process on ferrous and non-ferrous steel is able to increase wear resistance, corrosion resistance, toughness, and fracture toughness [Akincioğlu et al. 2015; Baldissera and Delprete 2008; Jovičević-Klug et al. 2020; Kalsi et al. 2010]. Cryogenic process causes more precipitation and uniform distribution of fine secondary carbides [Jaswin et al. 2010; Sonar et al. 2018].

In the field of tribology, cryogenic processes have long been investigated. The cryogenic process can change the microstructure and affect its characteristics, such as ductility, toughness, yield resistance, and corrosion resistance in tool steel [Thakurai et al. 2021]. Cryogenic process can also improve wear resistance because of formation of fine martensite [Meng et al. 1994]. The cryogenic treatment reduces the amount of retained austenite and increases the deposition of ultrathin carbides. The combination of deep cryogenic treatment and heat treatment can improve the performance of several types of steel. The high temperature in the austenizing process and the low temperature in the tempering process combined with the cryogenic process can improve the properties of the steel. The deep cryogenic treatment process causes carbide precipitation and matrix modification [Jovičević-Klug et al. 2021].

Several reports mentioned that cryogenic process is conducted on steel can increase both its hardness and toughness. Although the hardness increase is not significant, this process can also increase the toughness. The increase of hardness by 4.6% was obtained in the 80CrMo12 steel sample compared to the non-cryogenic sample [Amini et al. 2010]. Furthermore, Das et al. [Das et al. 2009] reported a 4.2% increase in hardness, while Haris et al. [Harish et al. 2009] obtained increased hardness of 14% on En31 bearing steel compared to no cryogenic treatment. Likewise, with the report made by Cakir and Celik [Cakir and Celik 2017] that the cryogenic treatment can increase the hardness and toughness of eutectoid steel. Yan and Li [Yan and Li 2013] further reported that the cryogenic treatment of tool steel was able to increase the toughness by 29%. The increase in impact toughness by cryogenic treatment is associated with the distribution of fine secondary spherical carbides, which divert and inhibit crack propagations. Meanwhile, the En52 material was able to increase the impact energy by 23% through cryogenic treatment compared to no treatment [Jaswin and Dhasan 2011]. The impact toughness of high-nitrogen steel plates can be correlated with Rolled homogeneous armor plates. High-nitrogen steel plates show better impact resistance than Rolled homogeneous armor plates [Bhav Singh et al. 2021].

The main parameters in cryogenic treatment are the cooling and heating rate, immersion period, cryogenic temperature, and cryogenic treatment sequence [Sonar et al. 2018]. DCT has been performed previously and immensely by researchers to increase the wear resistance and toughness of tool steel since DCT can improve the microstructure, hardness, and toughness properties. However, there is still no DCT application on steel plates as a candidate for ballistic-resistant material. Ballistic-resistant materials require a combination of hardness, tensile strength, and toughness. Therefore, this study aimed to determine and analyze the effect of immersion time on liquid nitrogen of medium carbon steel plate samples as candidates for steel plates that have been quenched and tempered on hardness, tensile strength, and toughness. This combination of hardness, tensile strength and toughness will be used as the base for ballistic testing and analysis at the next stage of the study.

METHOD

The preliminary study was conducted by the researcher using a steel plate with a thickness of 8 mm with chemical composition as shown in table 1 and it was cut into a piece with a dimension of 130 x 130 mm. The steel plate used here was the steel plate categorized in the medium carbon steel plate containing C of 0.4667%. Therefore, this steel plate can be hardened using heat treatment. A large proportion of element Si of 0.2441% as a carbide stabilizer could also increase the strength and hardness. The heat treatment process for austenitic steels using induction heating machine, quench, and temper was conducted on several variables, namely induction coil shape, induction coil dimension, induction frequency, austenite temperature, temper temperature, and ballistic test simulation. The analysis result of the study obtained that the optimization of hardness and toughness values was at the induction frequency of 46.69 kHz, austenite temperature 900°C quenched in the 15 liters of oil as a medium and tempered at 300°C [Purwanto et al. 2020a; Purwanto et al. 2020b; Purwanto et al. 2019; Purwanto et al. 2021a; Purwanto et al. 2021b].

Unsure	C	Si	Mn	Cr	Ni	Al	V	S	P	Cu	Co	Sb	Fe
%wt	0.466	0.244	0.558	0.055	0.041	0.016	0.001	0.01	0.020	0.057	0.01	0.006	balance

Table 1. Chemical Composition of Medium Carbon Steel Plate

In this activity, the most optimal plate resulted from quench temper in previous studies was processed with the deep-cryogenic treatment (DCT), and the impact on hardness, tensile strength, and impact toughness. The sample that had been applied the austenite process at 900°C, water quenching, and tempered at 300°C was made as a specimen for several tests, namely hardness test, tensile test, and impact test using a wire cutting machine. The test specimen was soaked in liquid nitrogen at -196ºC using a liquid nitrogen container as shown in Figure 1. The soaking was performed for 0, 1, 5, 10, and 20 days. Therefore, the scheme of heat treatment and DCT diagram is shown in the graphic in Figure 2.

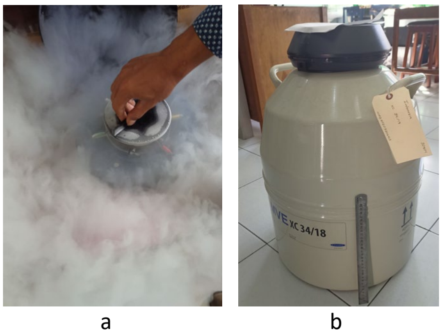

Figure 1. Deep cryogenic treatment a). Soaking process of specimen in a liquid nitrogen container b). nitrogen container

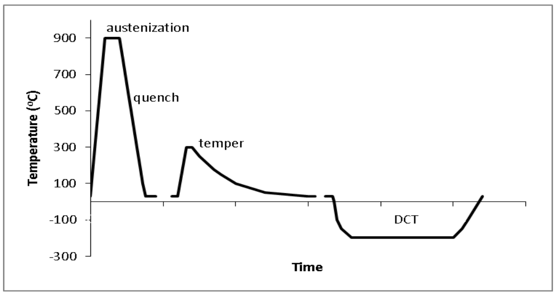

Figure 2. Schematic diagram of heat treatment and deep cryogenic treatment

The hardness test was conducted using the Micro Vickers method. The specimen for the tensile test was made based on the ASTM E8, while the specimen for the impact test was made based on the ASTM E23 as presented in Figure 3. The test specimen was taken from the median of each plate with a thickness of 8 mm.

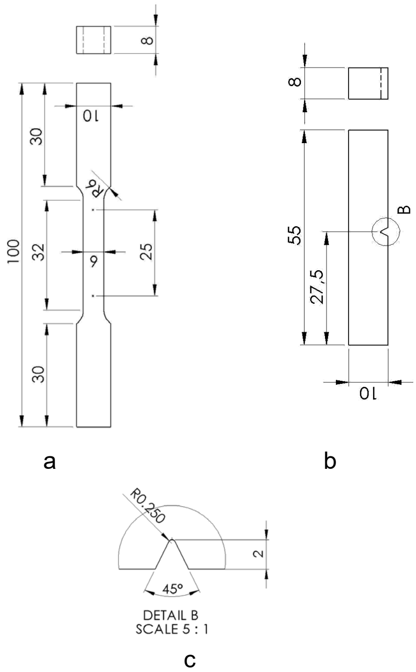

Figure 3. Test Specimens a). tensile b). impact and c). detail B

Each specimen in each variable was given a mark or code. The code was made to ease the process and marked each sample. The code was made based on the treatment process that had been conducted. The specimen code of heat treatment and DCT process is as presented in Table 2.

Code	Treatment	Explanation
RM	Raw Material	Commercial medium carbon steel initial material which was not treated
QT	Quench Temper	The treated material was heated at austenizing temperature of 900°C and tempering of 300°C
DCT1	Deep Cryogenic Treatment of 1 day	The treated material was heated at austenizing temperature of 900°C, tempering of 300°C and immersed in N2 for a day (24 hours)
DCT5	Deep Cryogenic Treatment of 5 days	The treated material was heated at austenizing temperature of 900°C, tempering of 300°C and immersed in N2 for 5 days
DCT10	Deep Cryogenic Treatment of 10 days	The treated material was heated at austenizing temperature of 900°C, tempering of 300°C and immersed in N2 for 10 days
DCT20	Deep Cryogenic Treatment of 20 days	The treated material was heated at austenizing temperature of 900°C, tempering of 300°C and immersed in N2 for 20 days

Table 2. Sample code and treatment

The microhardness testing was conducted in 20 points for each variable or 3 specimens. The load in the micro Vickers hardness testing machine was 0.5 Newton with a load duration of 10 seconds. The total specimen for the tensile test and impact toughness test was 3 specimens respectively for each variable. The tensile test was conducted using the Universal Testing Machine with a speed of tensile test of 20 mm/s. Meanwhile, the impact test was conducted using the Charpy Impact Testing Machine. The mean score of each testing result was calculated to be analyzed by calculating and considering the standard deviation.

RESULTS AND DISCUSSION

1. Microstructure

The microstructure of the raw material and the material that has been heat treated and DCT is shown in Figure 4. The material used is medium carbon steel, so that the ferrite and perlite phase can be seen. Pearlite is shown in the dark colored structure or phase and ferrite is shown in the lighter colored structure or phase, the structure looks smooth and uniform in both ferrite and pearlite (Figure 4.a). The quench process on medium carbon steel can transform the microstructure. It is seen that the change in the pearlite structure becomes more dominant and this will affect its physical properties. The martensite phase is not yet visible because more magnification is needed, but it is suspected that there is a martensite phase with a blade shape between the pearlite and ferrite phase (Figure 4.b). Figure 4c shows a structure that has been tempered, the structure looks coarser with a more dominant amount of pearlite. The DCT process on samples that have been heat treated also shows structural changes.

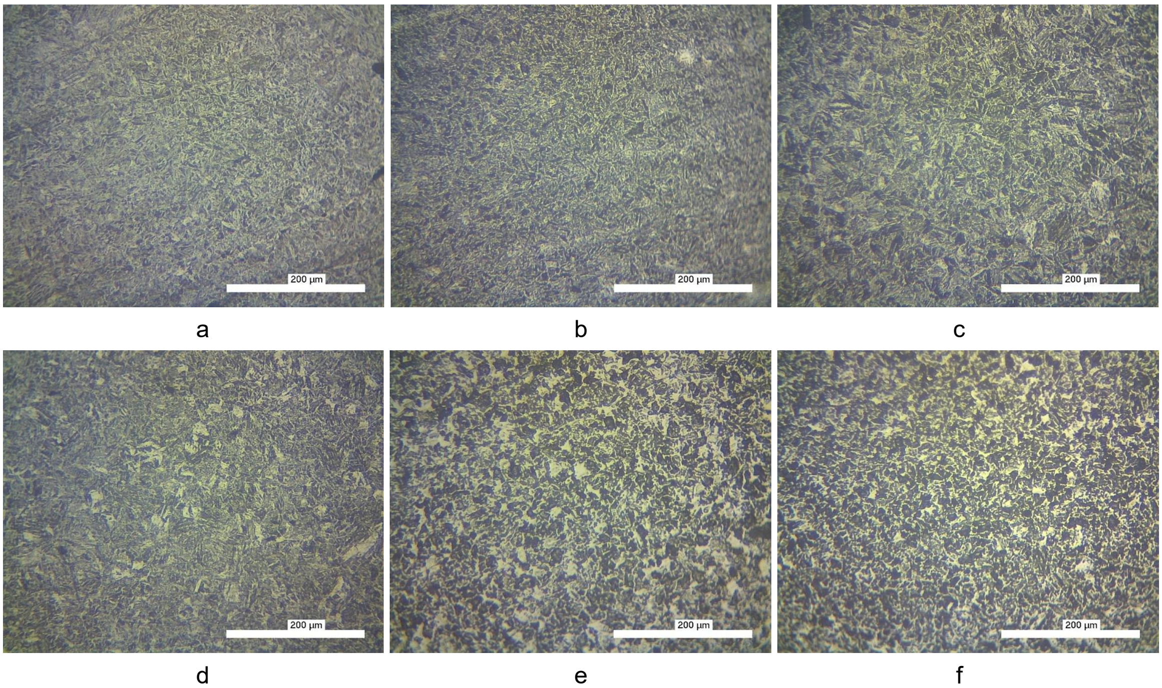

Figure 4. Microstructure a). raw material, b). quench temper, c). deep cryogenic treatment of 1 day, d). deep cryogenic treatment of 5 day, e). deep cryogenic treatment of 10 day and f). deep cryogenic treatment of 20 day

The structure of ferrite and pearlite looks different on DCT1 and DCT5 (Figure 4.c and Figure 4.d), cementite looks more spread out so the pearlite structure looks more even. The microstructure in DCT 10 and DCT 15 (Figure 4.e and Figure 4.f) the structure changed significantly, which tended to be blade-shaped, pointed and sharp to become more oval and sharp. And it gets smoother on the DCT 20 with a more dominant pearlite structure. This is due to the structure of cementite that is formed more and spread evenly. As stated by [Jaswin et al. 2010; Sonar et al. 2018] that the cryogenic process causes more precipitation and uniform distribution of fine secondary carbides.

2. Hardness

Hardness is one of the mechanical properties that affect ballistic resistance. High hardness has the ability to resist the rate of projectiles. The average Vickers hardness number for each treatment sample is shown in Figure 5.

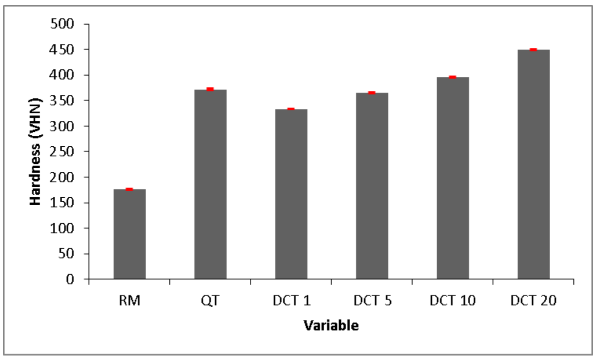

Figure 5. Average Vickers Hardness Number of each variation

Quench heat treatment which was followed by tempering process significantly increased the hardness. Quench process has the ability to change the steel phase from the ferrite and pearlite phases to a hard martensite phase [Purwanto et al. 2021a] and as seen in the Figure 4.b.

The hardness of the Raw Material obtained was 176.20 VHN, while the hardness of the quench temper increased to 371.81 VHN. This tempering process was done to remove residual stresses after the quenching process. The tempering process experienced a slight decrease in hardness, but since the residual stress was reduced, it can further reduce ASB and crack propagation when an impact occurs [Mishra et al. 2012]. Very hard materials tend to break easily. Hard material when exposed to ballistic loads will form holes with a plugging model [Zukas 1980] due to crack propagation [Mishra et al. 2013].

DCT treatment which was provided for 1 day caused the hardness to decrease to 333.59 VHN, while DCT treatment which was provided for 5 days caused the hardness to decrease to 367.75 VHN. This is the same as Thakurai et al. [Thakurai et al. 2021] which conducted a study on 40CrMoV5 tool steel, that the cryogenic treatment actually reduces the hardness and wear resistance. This also shows that the discussion about cryogenic treatment is debatable regarding its effectiveness [Sonar et al. 2018] for a period of less than 24 hours. However, when the DCT was conducted for 10 days and 20 days, the hardness increased significantly. After 10 days of immersion, the hardness became 396.69 VHN, while after 20 days of immersion, it became 449.45 VHN. Hardness at 20 days immersion increased 155% from Raw Material or increased by 21% from quench tempered samples. This shows that the longer the immersion time, the better the effectiveness of increasing the hardness. This increase in hardness is due to the precipitation of carbide and modification of the matrix which is finer and more homogeneous [Jo et al. 2020; Sonar et al. 2018], and also seen in the more even microstructure in Figure 4.e and Figure 4.f.. The maximum hardness obtained has exceeded the minimum standard of RHA armor material, namely 402 VHN, AR 500 armor steel [Jamil et al. 2016] and class 1 thin steel plate armor [MIL-DTL-12560K 2020].

3. Tensile strength

The increase in hardness in general also increases the tensile strength. The higher the hardness, the greater the tensile strength. The average yield stress, maximal stress, and elongation for each treatment variable are shown in Figure 6.

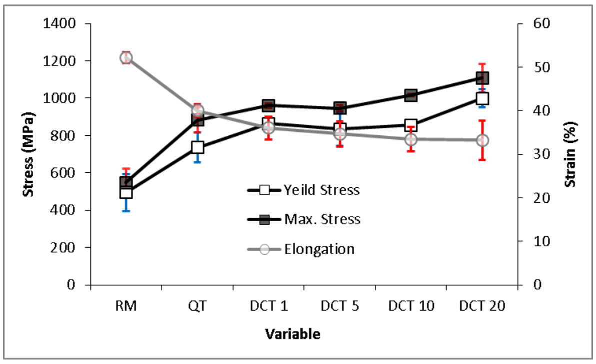

Figure 6. Average of yield stress, maximum stress and elongation Vickers hardness number on each variation

The raw material used was a medium carbon iron plate which has propertied of soft and ductile, so it has a relatively low tensile stress but high strain. This RM has yield stress of 491.13 MPa, Maximum stress of 548.01 MPa, and elongation of 52.15%. This material is easily penetrated by projectiles since the tip of the projectile easily pierces the target plate. The petaling hole model will be formed on the soft properties of the target material, low tensile strength, and high elongation [Zukas 1980]. The quench temper heat treatment increases tensile strength and decreases elongation. The yield stress of the steel plate that has been quenched increased to 735.92 MPa, the maximum stress also increased to 883.33 MPa, while the elongation decreased to 40.03%. These changes were caused by the phase change of ferrite and pearlite into martensite which is harder and stronger. With high hardness and high tensile strength, the ability to resist the projectile rate will be better. The tough and strong target material is able to resist and break the tip of a projectile at high speed [Purwanto et al. 2020c].

In contrast to the hardness that decreased during DCT process of 1 day and 5 days, the maximum tensile strength in this treatment increased even though it was relatively small. However, the yield stress has decreased. The phenomenon of increasing maximum stress and decreasing yield stress was due to a decrease in strain. Each yield stress on DCT 1, DCT 5, DCT 10, and DCT 20 was 863.85 MPa; 834.67 MPa; 854.45 MPa, and 998.99 MPa, respectively. Meanwhile, each maximum stress on DCT 1, DCT 5, DCT 10, and DCT 20 was 960.57 MPa; 946.94 MPa; 1015.81 MPa, and 1107.53 MPa, respectively. Furthermore, the elongation of DCT 1, DCT 5, DCT 10 and DCT 20 were 35.98 %, 34.64 %, 33.39 % and 33.23 %, respectively.

During the immersion of 20 days, there was a significant increase in tensile strength compared to the quench tempered sample. The maximum tensile strength of 20 days immersion increased by 25% compared to quench tempered material and increased by 103% compared to raw material. The increase in tensile strength is affected by the increase in hardness due to a smoother and more homogeneous martensite matrix and the occurrence of carbide precipitation on the martensite matrix. A significant increase in tensile strength was not accompanied by a significant decrease in strain. Although the tensile strength obtained is not in line with expectations, which is at least 1750 MPa [Jamil et al. 2016]. But this can be advantageous because the elasticity of the sample is still quite good. With elasticity that can be maintained, it is expected that the ability to absorb impact energy will be better. This is in accordance with the report submitted by Jena, et al. [Jena et al. 2010a] that ballistic resistance is the optimal combination of hardness, strength and impact toughness.

4. Impact toughness

Ballistic resistant materials are materials which have the capability of absorbing the impact energy of projectiles at very high speeds. The impact energy concentrated at the tip of the projectile must be able to be distributed over the entire surface of the target plate. So that cracking and perforation of the target plate perforation can be avoided. One indicator that can be measured is the impact test value of the impact test on the sample. The average impact test results on each variable are shown in Figure 7.

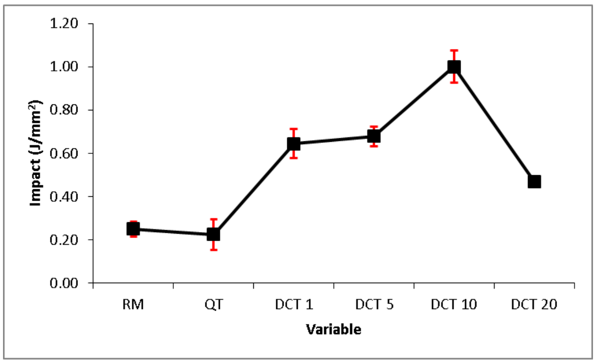

Figure 7. Average impact toughness on each variation

The average impact toughness of row material is 0.250 J/mm^2 and it decreased slightly after the quench temper heat treatment process to 0.225 J/mm^2. DCT process that was conducted on the sample caused the impact toughness to increase significantly. The maximum impact toughness occurred in samples that were immersed for 10 days, was 1,001 J/mm^2. However, there was a decrease in DCT for 20 days to 0.470 J/mm^2.

The increase in impact toughness was caused by carbide precipitation and modification of the matrix which was finer and more homogeneous [Jaswin et al. 2010; Sonar et al. 2018]. This impact toughness will affect the resistance to cracking and crack propagation if it is hit by a projectile. So that the emergence of ASB and ASB-induced cracking will be reduced and inhibited. Therefore, it can be predicted that its ballistic resistance will increase. Previous studies [Dogra et al. 2011], reported the DCT carbide turning tool steel material has the ability to increase wear resistance and is more resistant to impact between the tool and the workpiece.

The highest hardness and tensile strength were seen in samples treated with cryogenics for 20 days. Meanwhile, the highest impact toughness was obtained from the 10-day cryogenic treatment process. It is necessary to carry out further work using ballistic simulation and ballistic test experiments to find out the most appropriate combination of ballistic resistance, since the characteristics of ballistic resistance are an appropriate combination of hardness, tensile strength, and toughness of armor materials [Jena et al. 2010a].

CONCLUSION

Based on the experimental test that has been conducted and analysis results obtained, it can be concluded as follows:

1. Heat treatment and deep cryogenic treatment can change the microstructure, with deep cryogenic treatment The pearlite phase becomes dominant because the cementite structure is formed more evenly.
2. Deep Cryogenic Treatment has the ability to increase the hardness, tensile strength and impact strength. The maximum hardness produces during 20 days of immersion

were 449.45 VHN and 1107.53 MPa, respectively. However, the highest toughness was obtained during the immersion of 10 days, which is 1.001 J/mm². From the result of this testing, the impact hardness and toughness have fulfilled the requirements as RHA ballistic-resistant materials and armor steel plates. With high impact toughness, it is expected that it can dampen the projectile impact. Meanwhile, the standard minimum tensile strength of 1700 MPa is not achieved yet.

3. In order to obtain optimum combination of ballistic characteristics and ballistic limit, further experiment is necessary, either in terms of simulation using finite element method or ballistic experimental test.

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