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THE EFFECT OF CRYOGENIC TREATMENT ON THE PUNCH WEAR AND THE HOLE EDGE GEOMETRY

Summary

The ball joint parts made of forged steel are quite important in the suspension system. The quality of production of ball joint parts is very important because of their role. Some basic defects can be found in the hole edge form. These defects affect the hole quality of ball joint parts. In this study, the effects of cryogenic processing on the wear of AISI D2 punches and the effects of punch wear on the hole edge geometry of hot forged AISI 1040 steel ball joint parts were investigated. The hole geometry changes are generally associated with punch wear and process parameters. For the purpose of investigation, piercing was carried out using an eccentric press with AISI D2 tool steel punches on 6.0 mm-thick ball joint pieces. The punches were traditionally heat treated. Some of the punches were cryogenic-treated at -145 °C in addition to the conventional heat treatment. Weight loss values were measured to assess the punch wear, and SEM and OM images were analysed. At the end of the industrial piercing process, it was found that the D2 tool steel punch wear decreased with cryogenic process applied and the size changes in the hole edge geometry of the punched 1040 hot forged steel parts turned out to be less marked.

Key words: *Cryogenic treatment, ball joint, punch wear, edge geometry, AISI D2, AISI 1040*

1. Introduction

The suspension system carries the vehicle body and allows the driver and passengers to travel comfortably without transmitting all forces to them. This system of a car is used to support its weight under varying road conditions. The system is made of several parts and components, of which the ball joint is an important part (Fig. 1a). The ball joints are located between the wheel assembly and the chassis of the vehicle (Fig. 1b). Though there are many different metals and alloys that can be used, the most common ones are steel and aluminium because of their mechanical properties and price. Most of the components are made of metals and alloys. However, titanium and stainless steel can be used in important designs. Because of the importance of the ball joints, they are usually made of forged steel [1-6].

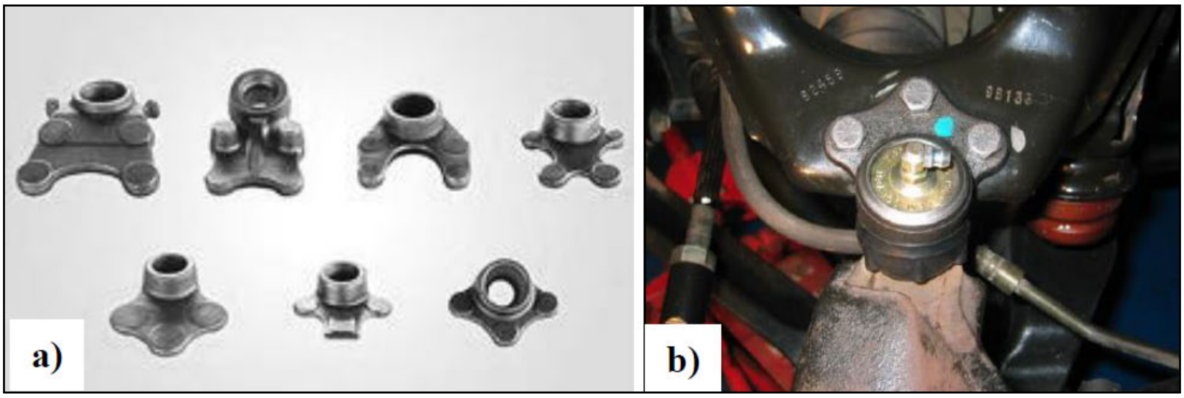


Fig. 1 **a)** Ball joint parts in various forms, **b)** A ball joint assembly [5, 6]

Forming with dies has an important place in the production in many sectors such as automotive. Developments in the die design and manufacturing have extended the die lifetime and increased the quality of punching and cutting by enabling a more precise and cost-effective production process. The cutting process during punching results in plastic deformation, cutting and breaking stages. According to studies in the relevant literature [6, 7], the punching parameters (type, thickness, die clearance, and piercing forces of the workpiece) directly affect the hole form (Fig. 2).

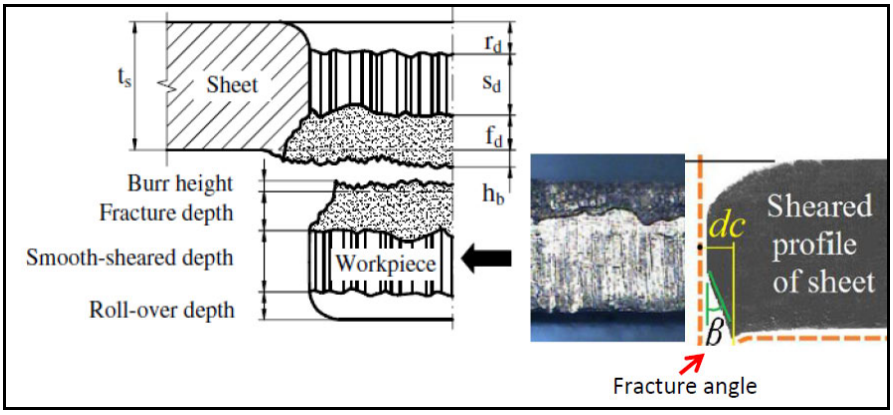


Fig. 2 Different zones of the part edge [8]

Long-lasting dies and punches, less waste, and better quality production are desirable on today's market. The quality of parts is affected by piercing parameters. The punch wear is generally assessed by criteria such as the geometry of the hole edge and the burr height. The rapid and excessive wear of punches can be influenced by the punch material and geometry [9-11]. Due to the mechanical properties of the workpiece and the punch material, excessive stresses and wear occur during the cutting process. These tribological phenomena can be explained as adhesion, transfer between friction elements and fatigue due to micro fractures. In order to maintain the hole quality when these phenomena occur, punches and dies must be replaced at optimum time [12, 13]. Corroded punches, which adversely affect the hole geometry, should be replaced at the appropriate time to control production costs [14]. A better geometry of the hole edge can be obtained by selecting the punching and cutting parameters of the punch and workpiece materials accordingly [15]. The tool life, wear, cutting clearance, and material thickness have been studied extensively in the relevant literature; however, the hole edge geometry of the products has not been studied yet [16, 17]. Traditional heat treatments are conducted to increase the production speed and the service life of die components made of tool steels (such as high-speed steel) being exposed to heavy loads. After traditional heat treatments, conducted in a way to cool tool steels to room temperature, there is still a significant amount of retained austenite in the microstructure. Although the mechanical properties and abrasion resistance are improved by heat treatment, the softer structure adversely affects the wear resistance during production. In recent studies, it can be seen that the traditional heat treatment in combination with cryogenic processes leads to a reduction in the amount of retained austenite in the microstructure of tool steels and increases their wear resistance [17-24].

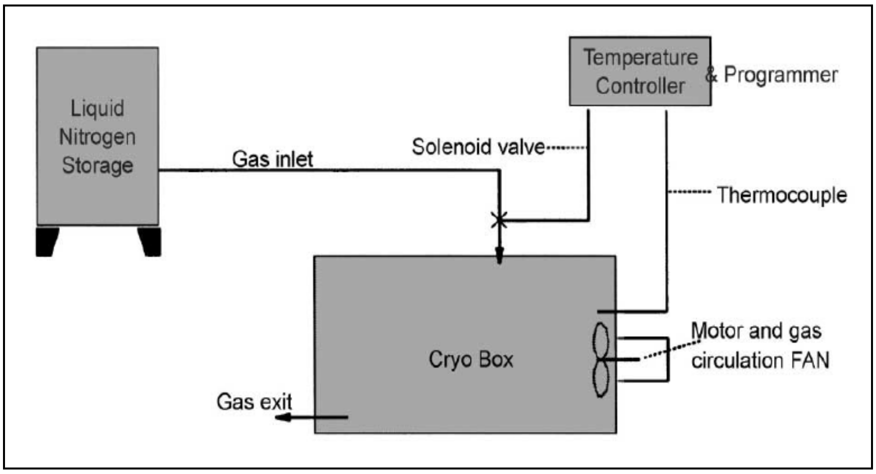


Fig. 3 A cryogenic system [22]

A cryogenic system is shown in Fig. 3. It has been reported that the cryogenic treatment applied after the conventional heat treatment contributes significantly to the wear performance of certain steels. The wear problems of high alloy steels used in important industries such as die industry have been reduced by cryogenic processing [25, 26]. The application of cryogenic treatment generally results in increased hardness and in the improvement of some of the mechanical properties. After this process, very fine carbide precipitation is observed in the tool steel microstructure with smooth distribution which turns into a martensitic structure and results in high hardness values. These improvements in tool steels have led to decreased wear. Moreover, in contrast to the coating process, the cryogenic process results in fine and dense carbide formation, with carbides uniformly distributed in the matrix structure [27-29].

The cryogenic process is performed once and at a low cost; it is usually carried out for 24 to 36 hours, at temperatures between -80 and -193 °C, with a cooling rate of 2.5 to 5 °C/min. The temperature is been gradually brought to ambient temperature by increasing and decreasing temperatures to avoid thermal shocks. There are a lot of studies on machining and cutting tools related to the effect of cryogenic processing. These studies generally focus on high alloy steels and tool steels [30-34]. However, no research has been conducted on the AISI 1040 hot forged steel ball joints and on cryogenically treated AISI D2 tool steel punches in industrial applications. Therefore, the effects of cryogenic processing on the wear of the D2 punches and the effects of punch wear on the hole edge geometry of the 1040 hot forged steel ball joint parts were investigated in this study. Moreover, this study has a real time industrial application.

2. Materials and Methods

AISI 1040 hot forged steel ball joint parts were used in this study (Fig. 4). The work pieces used in this study were made of 6.0-mm-thick AISI 1040 hot forged steel. The chemical content and strength values of a hot forged steel ball joint (as provided by the tool supplier) are presented in Table 1 and 2. The piercing processes were carried out using a 110 ton capacity press machine and 61 strokes per minute.

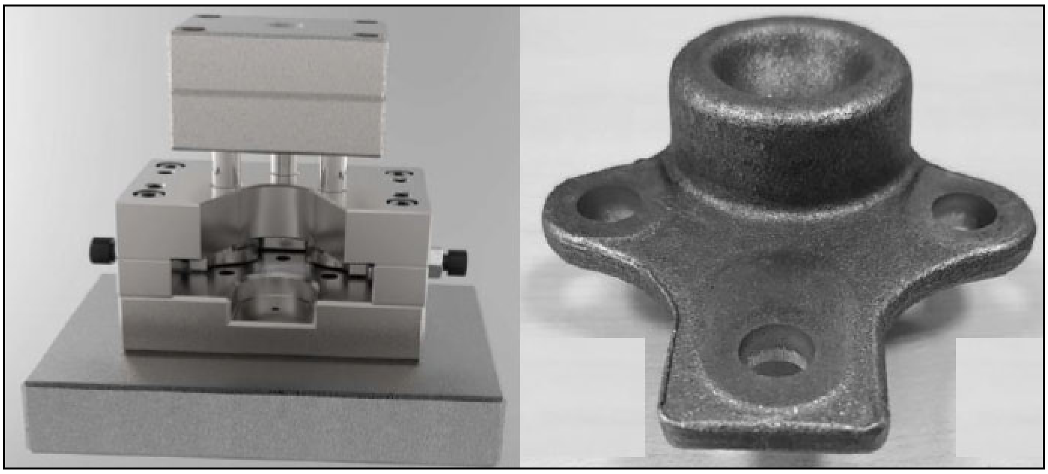


Fig. 4 The die of a ball joint and a ball joint part

The piercing operations were performed under dry conditions in this industrial application. The cutting clearance used in this study was 10% of the thickness of work pieces. The parts were measured at 1,000th, 5,600th and 9,000th strokes.

Table 1 Chemical composition of AISI 1040 steel

Elements (%)	C	Si	Mn	P	S	Al	Cr	Ni	Mo	Co
	0.427	0.209	0.630	0.011	0.0093	4.016	0.327	0.025	0.0037	0.0021

Table 2 Mechanical properties of AISI 1040 steel

Tensile strength (N/mm^2)	Yield strength (N/mm^2)	Hardness (HB)	Elongation (%)
600	361	188	25

The punches were designed to have Ø 8.5x100 mm. They were made of AISI D2 tool steel. Table 3 presents the chemical composition of that tool steel while Table 4 shows its mechanical properties (provided by the supplier of punches).

Table 3 Chemical composition of AISI D2 cold work tool steel (soft annealed)

Elements (%)	C	Si	Mn	P	S	Cr	Mo	V	Ni	Cu
	1.590	0.360	0.500	0.025	0.006	12.430	0.870	1.000	0.240	0.080

Table 4 Mechanical properties of AISI D2 cold work tool steel (soft annealed)

Tensile strength (N/mm^2)	Compressive yield strength (at 62 HRC) (N/mm^2)	Hardness (HB)	Density (gr/cm^3)
940	2200	225	7.67

In this study, punch tools were exposed to deep cryogenic treatment (DCT) after conventional heat treatment (HT). The HT of the D2 tool steel involved hardening and tempering. On the other hand, the DCT of the D2 steel involved hardening and cryogenic treatment before annealing (Fig. 5). DC samples were treated by the conventional heat treatment and deep cryogenic treatment. But, no tempering was performed after the cryogenic treatment. HT and DCT samples were used in the piercing process. The HT of the D2 tool steel was carried out using 4 bar nitrogen in the vacuum heat treatment furnace. The vacuum method is a common process used in industry. In order to eliminate the harmful effects of the gases in the air, hardening was conducted in a vacuum atmosphere [35-39]. In the DCT operation, HT samples were gradually cooled to -145 °C at a cooling rate of about 5 °C per minute. The samples were kept at this temperature for 36 hours. After the samples had been gradually reheated to room temperature (at the same rate as in the cooling process), tempering operations were performed. A schematic of the heat treatment of the AISI D2 punches is given in Fig. 5.

A HOYTOM 1003 test machine was used for the evaluation of macro hardness of the samples prepared in accordance with the standards. The main load of 1.5 kN was applied for 20 seconds after a preload of 0.1 kN. The average of five measured values was used as the hardness value. The measurements were performed at Rockwell hardness (HRC). The micro-hardness values were read after applying a 3 N load for 15 seconds. This process was repeated 10 times. The measurements of Vickers hardness (HV) were performed using a DUROLINE-M model measuring device.

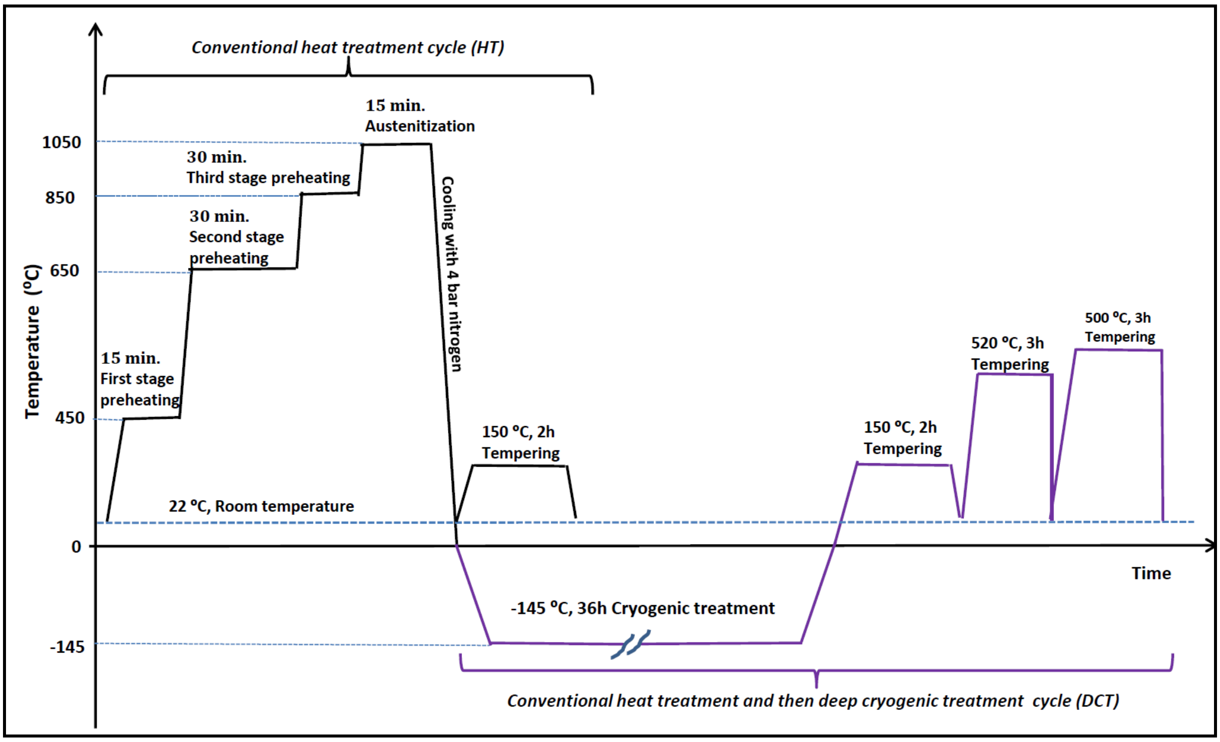
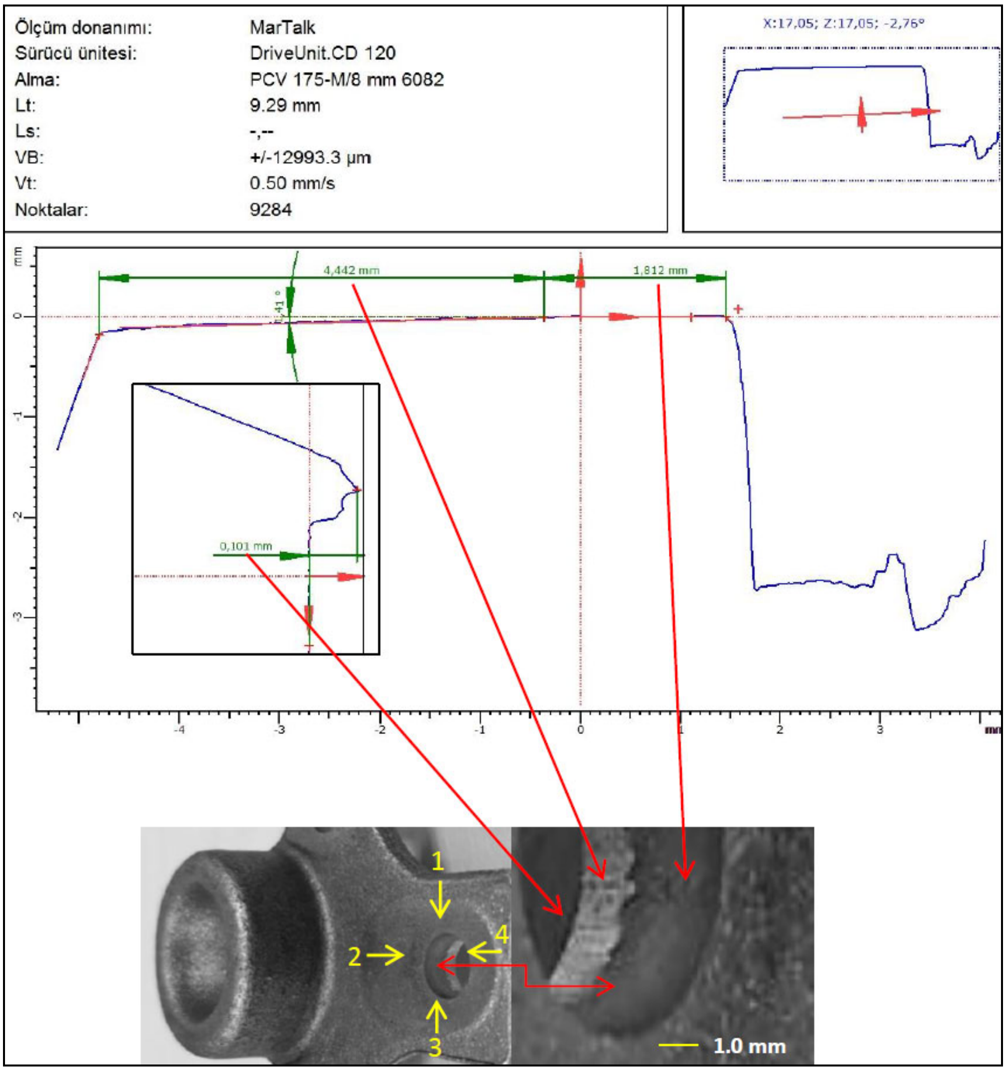


Fig. 5 Schematic of the heat treatment of AISI D2 punches

Microstructural examination was performed using a FEI Quanto FEG 250 scanning electron microscope (SEM). X-Ray Diffraction (XRD) analyses were made in order to determine variations in the microstructure caused by deep cryogenic treatment. Analyses of the retained austenite were conducted according to the ASTM standard E975-13. For the microstructural studies of AISI D2, samples were ground between 80 and 1200 mesh SiC papers according to metallographic preparation standards. Then, they were polished with a polishing solution (diamond paste) and were etched three times with 2% Nital solution for 10-20 seconds.

Values of the weight loss of the punches required for assessing the wear resistances were measured on a sensitive scale (ELE L 200S Sartorius Laboratory with a sensitivity of 1×10^{-3} g). The weight loss values of the punches were measured at 1,000th, 5,600th and 9,000th strokes. They were measured after cleaning. This process was repeated three times. Further, the degrees of wear of the punches were defined by an Optical Dino-Lite Digital Microscope (OM) Pro2 and by SEM images at the end of the process.



Ölçüm donanımı:	MarTalk
Sürücü ünitesi:	DriveUnit.CD 120
Alma:	PCV 175-M/8 mm 6082
Lt:	9.29 mm
Ls:	-,--
VB:	+/-12993.3 µm
Vt:	0.50 mm/s
Noktalar:	9284

Fig. 6 Outputs of the contour measuring machine

For the measurement of the cut surface holes, a MarSurf CD 120 contour measuring machine with a sensitivity of 1×10^{-3} mm was used. Thus, no damage was done to the ball joint parts by measurements. The outputs of contour measuring machine are shown in Fig. 6. About 100 ball joint parts were taken for measurements at the end of each stroke. In order to determine the geometry of the cut surface edges of three ball joint parts selected from 100 samples, four different regions of the holes of each part were measured. The average of the recorded values (s_d smooth-sheared value, f_d fracture value, and h_b burr value) was obtained. The rollover depth (r_d) is calculated by Equation 1 using the values read from the measuring machine and the value of sheet thickness (t_s) (Fig.6) [7, 24, 40].

$$r_{\mathrm{d}}=t_{\mathrm{s}}-[(s_{\mathrm{d}}+f_{\mathrm{d}})-h_{\mathrm{b}}] \tag{1}$$

3. Results and Discussion

The effect of cryogenic treatment on hardness values can be seen in Fig. 7. The DCT resulted in an increase in the macro hardness and micro hardness values of AISI D2 tool steel by approximately 3.1% (HR_C) and by 7.99% (H_V), respectively (Fig. 7). Although higher hardness values were obtained for DC samples, their toughness was very poor, which might cause brittle fracture during the piercing process. Thus, DCT samples were preferred to DC samples in application.

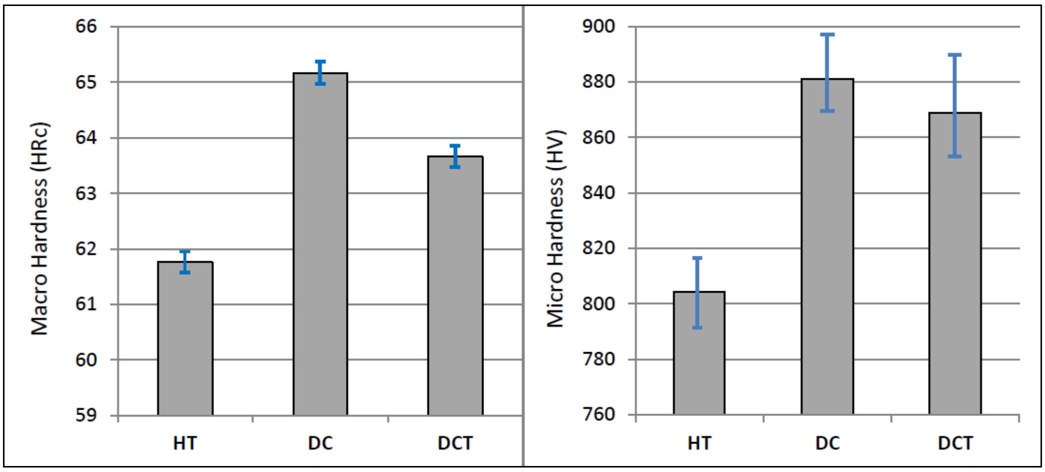


Fig. 7 Macro and microhardness test results of the AISI D2 tool steel

The study showed that the holding time was one of the major factors affecting the material properties and microstructural changes. Similarly, new carbides formed in the microstructure, and the cryogenic process provided a more uniform distribution. Moreover, the austenite retained in a significant amount in the microstructure can be transformed to martensite. These changes in the structure resulted in an increase in the hardness of the samples. Molinera et al. studied the cryogenic process of the M2 and H13 tool steels and found that their hardness increased by about 3% to 5.8% [22].

The cryogenic process increased the martensite conversion and led to new thin carbide precipitates (Fig. 8a and b). A decrease in the amount of retained austenite and an increase in fine carbide formation led to increased hardness. Findings in the relevant literature support the results of this study. [27, 30, 34, 38-41].

Figure 8 shows the microstructure of the samples selected to investigate the effects of cryogenic process on the D2 tool steel. In the figure, one can see that the primary carbides (PCs) and secondary carbides (SCs) are more evenly distributed because of the cryogenic process. Moreover, the cryogenic treatment reduced the size of primary particles and increased the volume fraction of secondary carbide particles (Fig. 8a and b). In a number of studies, it has been reported that the cryogenic process not only produces more intense SCs in the microstructure of steels, but also finer PCs [20-23, 26, 27, 37-42].

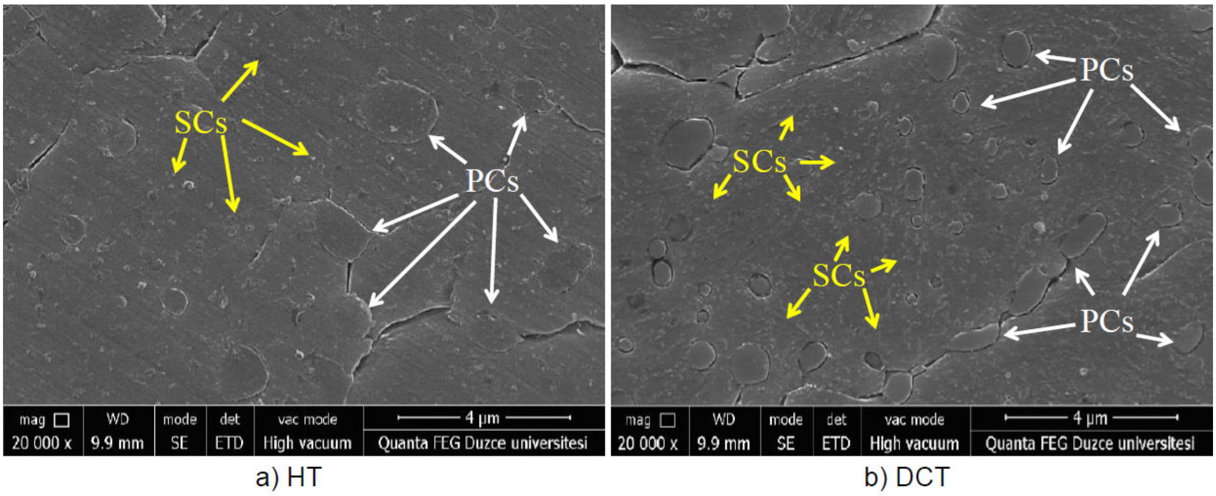


Fig. 8 Microstructure of the AISI D2 tool steel

Figure 9 shows the results of the XRD analysis performed to determine the amount of retained austenite in the D2 tool steel according to the ASTM standard E975-13 after cryogenic processing. The results show that the amount of retained austenite was dramatically reduced to 1.2% by the cryogenic treatment; this is due to 92% martensite transformation resulting from the cryogenic treatment. The results differed only slightly after the DCT process. They show that the deep cryogenic process of the D2 tool steel caused a significant change in its microstructure. Studies in the literature report that the cryogenic process positively affects the wear resistance and enhances the mechanical response of materials due to the change in their microstructure, where the retained austenite provides martensite transformation and newly formed carbides are homogeneously distributed [37, 38, 43-45].

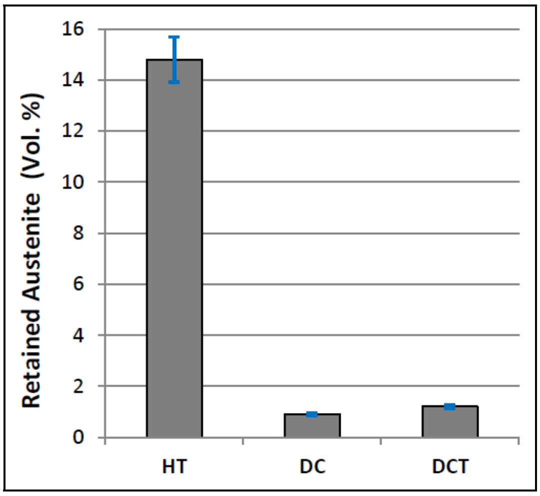


Fig. 9 Retained austenite of AISI D2 tool steels

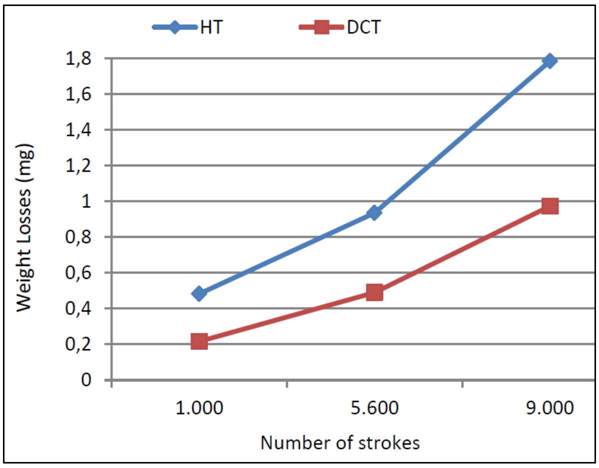
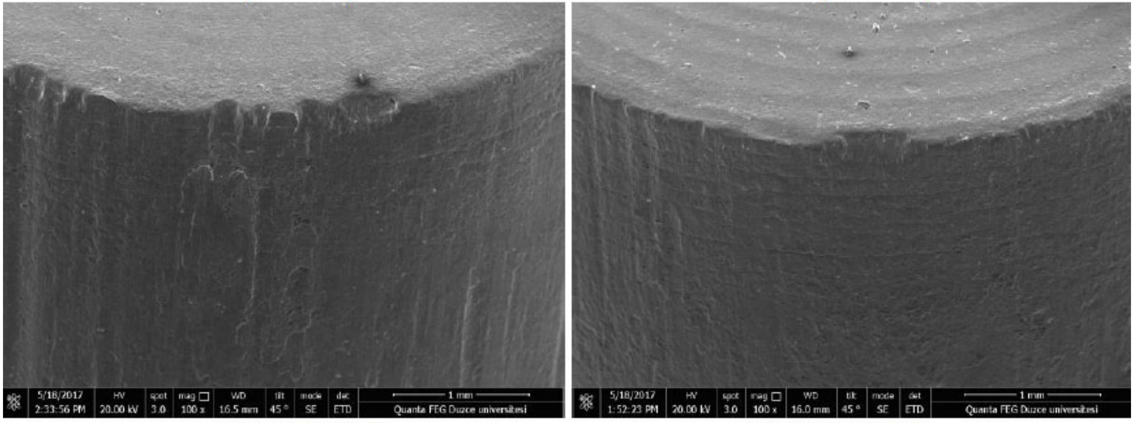


Fig. 10 The relationship between the weight loss and the number of strokes

The weight losses of punches in the piercing stages are shown in Fig. 10. The DCT punches showed less wear in all piercing stages. The HT punches exhibited higher wear weight losses by approximately 83.4% than the other two groups of punches. It can be said that the cryogenic treatment significantly decreased the weight loss and hence improved the wear resistance and tool life of the tested punches. Similar results are reported in relevant literature [17-19, 26, 27, 30, 33, 37].

The types of surface wear of the punches were identified by OM and SEM images in all piercing stages. The adhesive and the abrasive wear on punch cutting surfaces, as well as the fatigue wear and microcracks were determined through OM and SEM images. There were more microcracks in the HT punches (Fig. 11). Fatigue microcracks were more common at the cutting edge of the HT punches. Fatigue is a progressive and slow-acting failure of components. Fatigue behaviour of materials is affected by various parameters [46, 47]. The abrasive wear was generally observed in the DCT punches; however, adhesive wear was observed on the surfaces of HT punches (Fig. 11). It has been reported that the chromium in the material structure is responsible for the adhesive wear [14].

HT (OM x50) DCT (OM x50)



HT (SEM x100) DCT (SEM x100)

Fig. 11 The edge and face wear of the punch at the end of strokes

The effects of cryogenic treatment on the quality of the surface and the hole are shown in Fig 12. It can be seen that the number of strokes affects all parameters. Increased stroke numbers resulted in more severe deterioration. Similarly, the rollover depth and the burr height were significantly reduced by the DCT. However, the smooth-sheared depth and the fracture depth were not affected by the cryogenic treatment. In addition, the average fracture angle increased in the DCT punches.

The important factor in the quality of the hole after piercing is measured by the hole diameter, circularity, rollover depth, fracture depth, burr height, fracture angle, and smooth-sheared depth [48-51]. In the holes produced by the HT punches as compared to the DCT punches, the following was observed: the rollover depth, burr height, and fracture angle increased by 54%, 27.3%, and 5.1%, respectively, but the fracture depth decreased by 2.5%. The test results show that the cryogenic treatment enhances some mechanical properties and improves the product quality because of a lower degree of wear of punch surfaces.

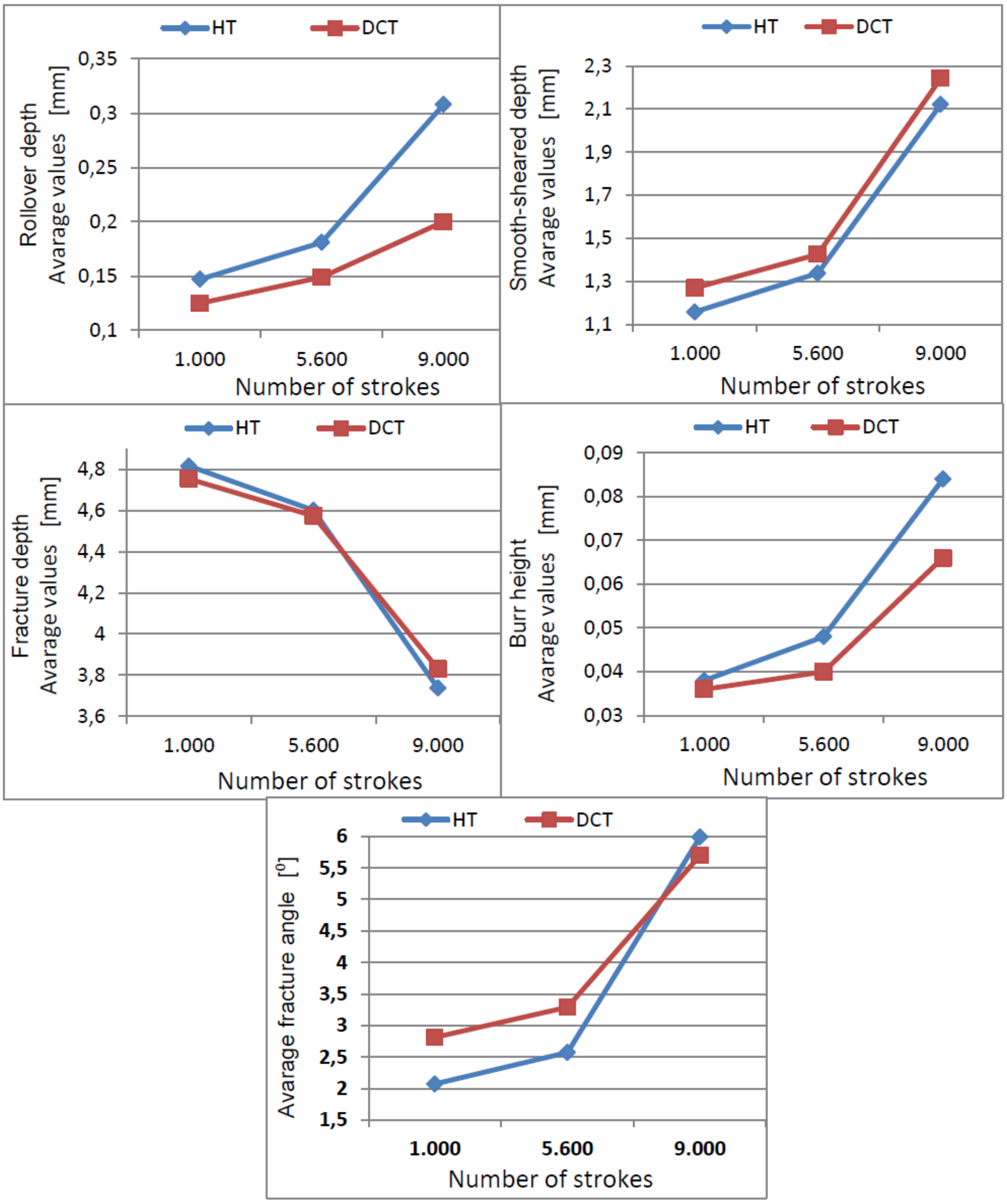


Fig. 12 Average values of geometry of the cut surface of the holes of ball joint parts

4. Conclusions

The industrial application of the AISI D2 tool steel punches and the AISI 1040 hot forged steel ball joint parts was tested and the following results were obtained:

1. Hardness values were affected by cryogenic treatment due to the microstructural changes.
2. The amount of retained austenite was dramatically reduced by the cryogenic treatment to 1.2%, which result from 92% martensite transformation occurring during the cryogenic treatment.
3. The primary and the secondary carbides were more evenly distributed in the microstructure due to the cryogenic process.
4. The DCT punches were less worn in all piercing stages. The wear weight losses of HT punches were approximately 83.4% higher than of DCT punches.

5. The abrasive wear was generally observed on the DCT punches; however, adhesive wear was generally observed on the surfaces of the HT punches.
6. In the holes produced by the HT punches as compared to those produced by the DCT punches, the following was observed: the rollover depth, burr height, and fracture angle increased by 54%, 27.3%, and 5.1%, respectively, but the fracture depth decreased by 2.5%.

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