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An investigation of the hole diameter and circulirty on the stainless steel sheet perforated via by deep cryogenically treated cold work tool steel punches

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Abstract
Because of punch wear increases finished hole errors, Hole quality and punch wear are closely related. This phsical errors can be found on the surface of the part and characterise its quality and accuracy. Punch errors are substantialy related with punch wear and process parameters. The purpose of this work was to investigate the effect of cryogenically treated punches on AISI 304 austenite stainless steel sheet piercing hole errors. In accordance with this purpose, the punching was carried out in a punch machine using 5, 6 and 7 mm diameters of AISI D3 cold work tool steel punches and 1.5 mm thick stainless steel sheets. One punch group in 36 hours was subjected to the deep cryogenic process at -145°C in addition to the conventional heat treatment. The deep cryogenic process was carried out to improve the wear resistance and hole quality. For this work, punch weight losses were measured and punch wear was evaluated through analysis of SEM and OM images. The hole diameter and circularity of the selected products were measured in the specified number of perforation AISI 304 austenite stainless steel in the CMM. Results showed that the deep cryogenic process applied to the punches was shown to increase the punch wear performance. Moreover, it increased the part quality by having a positive effect on the hole quality of the AISI 304 austenite stainless steel workpieces.

Keywords: Cryogenic treatment; perforation; punch wear; hole quality; circularty

1. Introduction

At the present time, the die design and making industries are very important in the supply chain to obtain a new product at low costs. In addition, considering industrial competitiveness and short product life, the requirements on production times and lower costs of machining processes are of significant importance [1]. Punching and blanking are the most common used in sheet metal production. This operation consists of cutting a sheet of metal by subjecting it to shear stresses. The process is widely used in the production of sheet metal components in the automotive, electrical, electronic, chemical, tool manufacturing and other high productivity industries. The sheet metal blanking and piercing industry is facing an increasingly competitive global market. Thus, in order to compete in this market, the need has arisen to obtain longer punch life, higher stroke rates and better quality parts. The quality and accuracy of the workpiece are evaluated by the geometry of the cutting edge of the blanked part surface and depend on many factors such as tool design, punch material properties, stamping conditions and especially punch wear [2-5]. In particular, extreme wear causes incorrect geometry in the cut parts, which can be scrap [6]. The punch is exposed to the strong tribological loads of the sheet metal blanking and piercing process. Punches frequently show adhesive and abrasive wear on the cutting edges. Tool wear generally occurs on the face, edge, and side of the tool. It is commonly observed that the overall rate of tool wear increases with decreasing clearance. Failure analysis and improvement of cutting tool life and tool wear are included in researchers interest in recent years [7-19]. The tool wear in piercing is an important cause for the worse geometry of piercing parts. Furthermore, the wear also results in the failure of the tool, causing unexpected end of die performance and increased production costs of piercing. In the punching process, some factors such as the clearance, the punch speed, the tool geometry, the lubrication and the mechanical properties of the material affect the quality of the final workpiece

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cutting edge geometry [10-13]. A lot of study has been done to find the optimum clearance value for different materials, different thicknesses and clearances [12, 14-16]. However, there has been little research investigating the relationship between punch wear and the final hole quality.

Most die materials are subjected to extremely high loads in the form of rapidly applied punches. Therefore, many die components are made of tool steels. The tool steels are used in a conventionally heat treated state. The heat treatment imparts desirable properties such as increased hardness and high wear resistance. But, with the conventional heat treatment of tool steels through quenching and tempering, the retained austenite content in the tool structure is in a soft phase, unstable at low temperature and transformed into frangible martensite during processing. With the high carbon contentin alloyed steels, the martensite finish temperature is below 0°C, which means that after the heat treatment, a low percentage of austenite is still retained at room temperature. These problems can be resolved by using cryogenic treatment to transform the retained austenite into martensite [5, 17-22]. One of the new methods to enhance the characteristics of tool and components are treating cryogenic temperatures known as cryogenic treatment. Cryogenic treatment is a supplementary process for conventional heat treatment. It is an inexpensive one time treatment that affects the core properties of the component, unlike merely surface treatments. Research has shown that cryogenic treatment increases product life and, in most cases, provides additional qualities to the product, such as stress relieving and dimensional stability [19–21, 23]. The most significant change as reported by the author is the transition of relatively soft retained austenite to the harder and more durable martensite. The researcher supported his claim by citing the example of 52100 carbon steel, in which cryogenic treatment results in almost 99% conversion of retained austenite to martensite [19, 25, 26]. Researchers believe that cryogenic treatment promotes the transformation of retained austenite into the martensite matrix as well as the formation of fine carbides and their uniform distribution in the matrix. They also believe that cryogenic treatment can contribute to enhanced wear resistance and other properties of the steels such as hardness and strength [5, 17, 22-26]. Most of the well documented studies on cryogenic treatment of machining and cutting tool materials have focused mainly on tool steels, in particular on high-speed steel [20-22, 25, 27-30]. However, few studies has been done on the performance of AISI D3 cold work tool steel in sheet metal production.

In this work, the aim was to investigate the influence of punch wear on the hole geometry of the piercing workpiece. Additionally, it was to examine the influence of cryogenic treatment on punches made of AISI D3 tool steel further the relationship between punch wear and the hole quality of the AISI 304 austenite stainless steel workpieces.

2. Materials and methods

2.1. Piercing experiments

Experiments were carried out using a TRUMP TR 240 punch machine with a speed of 160 strokes/min. These piercing tools were made of AISI D3 cold work tool steel (Fig.1). The punch tool was designed to piercing circular parts of 5, 6 and 7 mm in diameter (Fig.2). The workpiece material used in the study consisted of 1.5 mm thick AISI 304 austenite stainless steel sheets in dimensions of 500×500 mm.

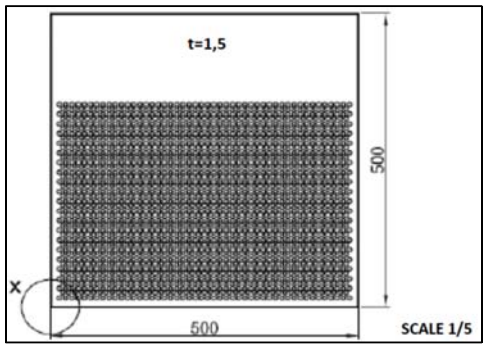
The compositions (wt%) of the sheets is given in Table 1. The initial yield strength and the tensile strength of the sheet metal were 215 N/mm² and 505 N/mm², respectively (Table 2). The piercing operations were performed under dry conditions. The cutting clearance used in this study was 12% of the sheet thickness. The measurements were performed at the end of the 6,000th, 12,000th, 18,000th, 24,000th, 30,000th and 40,000th strokes.

2.2.Cryogenic treatment

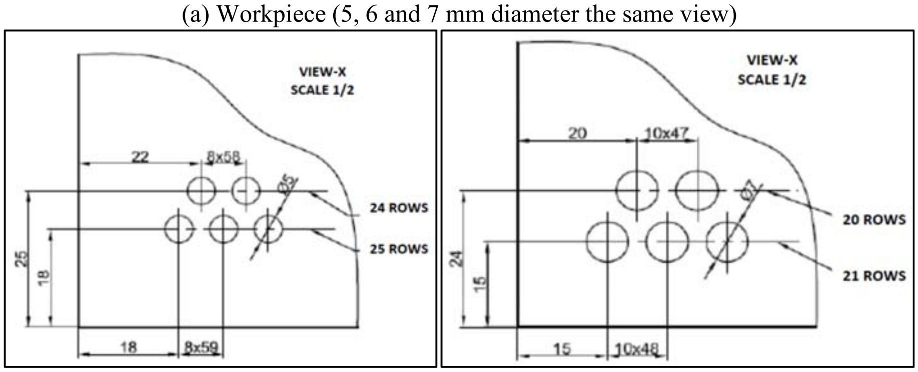
The punches are made of a commercial AISI D3 tool steel. The chemical composition (wt%) and mechanical properties of AISI D3 tool steel are given in Table 3 and 4.

The samples of tool steel were usually subjected to cryogenic processing by cooling the punches from room temperature to -196□, holding the punches at -196□ for different durations such as 36 and 84 h, and finally heating the samples back to room temperature. The samples were then tempered at a suitable temperature for some time [26, 31, 32]. The used cryogenic system and equipment is given in Figure 3.

Figure 1. AISI D3 tool steel punch and die (5, 6 and 7 mm).



(a) Workpiece (5, 6 and 7 mm diameter the same view)



(b) Layout of the holes on the specimens (6 and 7 mm diameter the same)

Figure 2. Details of the specimen used in piercing tests (5, 6 and 7 mm diameter).

Table 1. Chemical composition of AISI 304 stainless steel

Material / (wt%)	C	Mn	Si	Cr	S	P	Ni	Balance / Fe
AISI 304 Austenitic	0.58	1.62	0.15	19.06	0.03	0.09	9.67	68.81

Table 2. The mechanical properties of AISI 304 stainless steel

Tensile strength (N/mm^2)	Yield strength (N/mm^2)	Hardness (HRB)	Density (gr/cm^3)
505	215	70	8

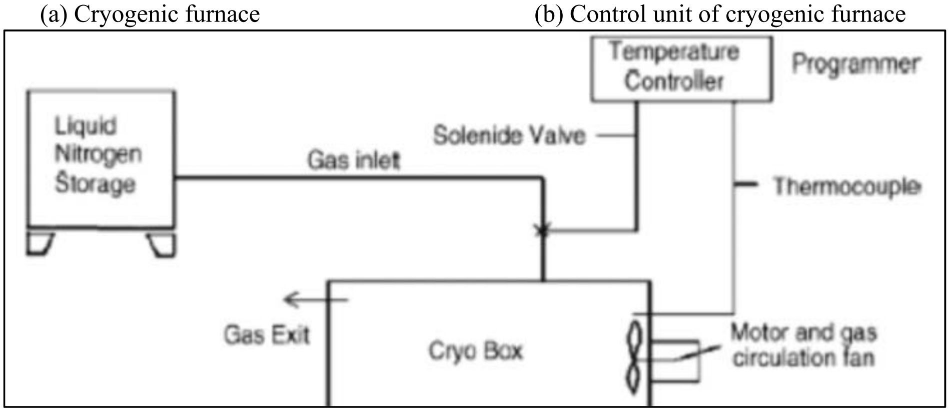
Table 3. Chemical composition of AISI D3 tool steel

Material / (wt%)	C	Mn	Si	Cr	S	P	Ni	Balance / Fe
AISI D3	2.09	0.17	0.01	12.35	0.001	0.015	0.21	85.14

Table 4. The mechanical properties of AISI D3 tool steel

Tensile strength (N/mm^2)	Yield strength (N/mm^2)	Hardness (HRB)	Density (gr/cm^3)
970	850	28	7.86

(a) Cryogenic furnace (b) Control unit of cryogenic furnace



(c) Cryogenic equipment [5]
Figure 3. The cryogenic system and equipment.

The punch tools were subjected to conventional heat treatment (HT) and then cryogenic treatment (CT). The heat treatment for the AISI D3 punch tool steel involved hardening and tempering [26, 30]. The hardening and cryogenic treatment schema is given Figure 4.

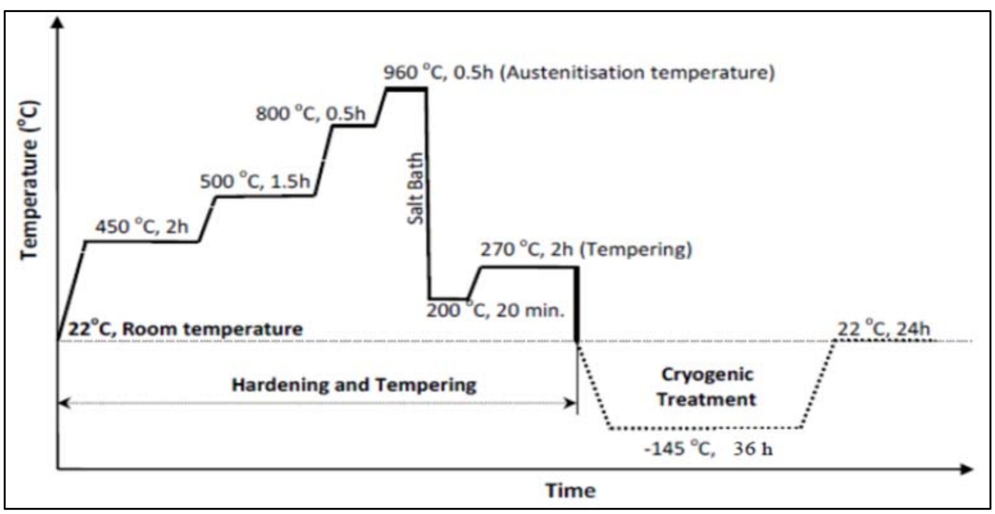


Figure 4. A schematic presentation of the heat treatment schedule consisting of the hardening, tempering, deep cryogenic treatment and tempering cycles of the punches.

In this study, the cryogenic treatment (CT) consisted of the cooling of the HT samples by gradually lowering them to nearly -145°C at a rate of 5°C per minute, holding them constant at this low temperature for 36 h and then gradually returned them to room temperature [5, 19, 26, 31-33].

2.3. Macro and microhardness measurements

For the hardness measurements, a Rockwell hardness tester was used. The samples were prepared according to test standards [5, 26, 31-36] and the Hoytom 1003 testing machine was used to evaluate the AISI D3 tool steel material on the HRC scale. A minor load of 0.1 kN was initially applied to seat the sample and for the HRC measurement the major load of 1.5 kN was then applied for a duration of 20 s. The indicator values were recorded and averaged. The microhardness of the samples was established by the DUROLINE-M micro hardness tester. The Rockwell indenter with a load of 5 N and 15 s dweel time was used as the indenter of the tester. Each hardness test was carried out 10 times to obtain a reliable result.

2.4. Microstructural examination

For the metallographic analysis, the samples were prepared according to the metallographic rules [5, 26, 31-36]. Initially, the specimens were burnished using 80-120-200-400-600-800-1000 and 1200 grit emery paper and then polished using diamond paste on a turning velvet disc (1 mm/2 min) in order to ensure a surface free from scratches. In the end, mirror finishing of the AISI D3 tool steel was done on a velvet cloth burnishing machine with a suspension of fine discontinuous alumina. This solution was used for revealing microstructural constituents of the AISI D3. The 2% Nital solution was composed of 98% CH_3OH and 2%HNO_3 using the solution, each sample was etched three times for between 20 and 30 s. Microstructural analysis was carried out on images taken by the FEI Quanto FEG 250 scanning electron microscope (SEM). In addition, at the end of each cycle, the face wear of the punch was determined via SEM and optical stereo microscopic (OM) images.

2.5.Weight loss on the punch

The weight loss measurements on the punch were made after 40,000 stroke punch cycles. For this purpose, a precision balance (ELE L 200S Sartorius Laboratory) with a sensitivity of 1×10-3g was used. The wear loss of the punches during the blanking perforation was measured in order to find the wear resistance of the materials. First, the punches were cleaned with acetone, and then air was blown onto the punches. After the punches were cleaned, they were put on the precision balance. The weight loss of each punch was taken three times to assure reliable results [5].

2.6.Measurement of the hole

For the image of the flank face in the hole, Dino-Lite Digital Microscope Pro2 images were used. The flank face length of the hole was measured at 1 mm via OM. The image for the flank face in the hole of the workpiece defined in this study are shown in Figure 5. The different zones of the blanked part edge are shown in Figure 6. The geometries of the hole on the puncture part examined in this work include the hole diameter (Ø d) and circularty.

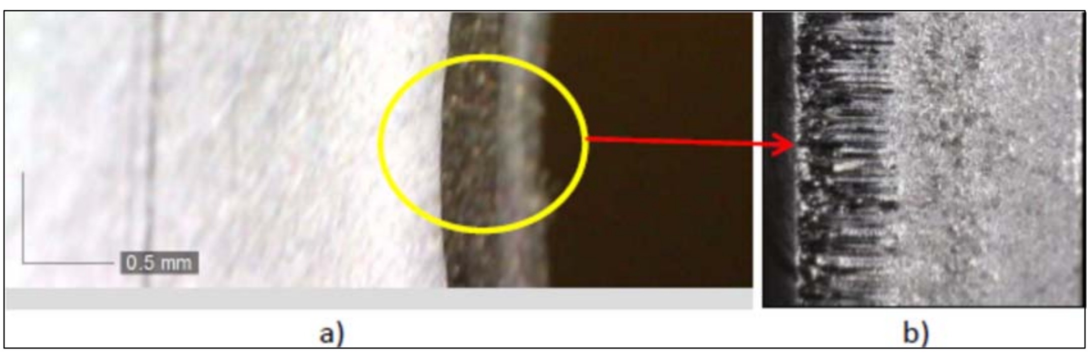


Figure 5. The OM image of the flank face in the hole (a: oblique view by 45°, b: view by 90°).

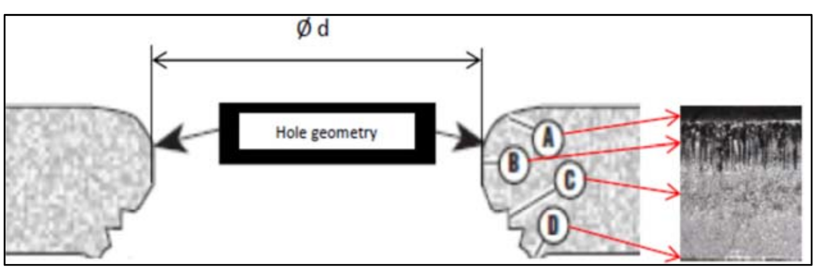


Figure 6. During the punching process for piercing sheet material formed in line geometry (Ø d: Hole diameter, A: Rolling, B: Shear flat, C: Fracture, D: Burr).

The hole diameter and circularty error values were measured using a LK Integra 10-7-6 Digital three-dimensional coordinate measuring machine device (CMM) with a measurement sensitivity of 0.001 mm. The schematic presentation of the circularty and circularty error of holes is given Figure 7.

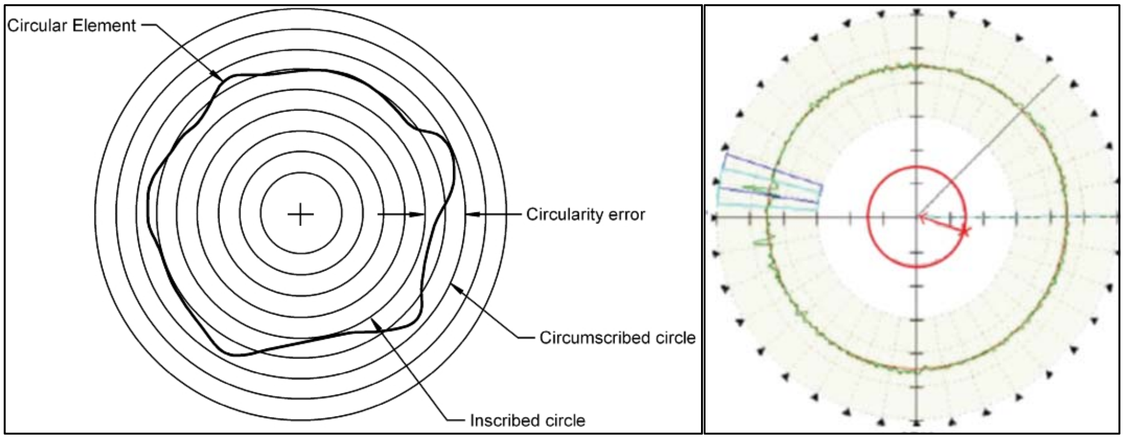


Figure 7. A schematic presentation of the circularty and circularty error [1]

For the measurements, about ten sheet workpieces were taken at the beginning of each cycle [5, 34]. Then 100 holes were randomly chosen out of 10 holes. Minimum six points were measured to obtain the hole diameter and circularity error at a certain depth of the hole in the shear flat of hole geometry. The hole diameter and circularity of the selected perforation were measured in the specified number of perforation AISI 304 austenite stainless steel in the CMM (Fig. 8). Their average values were obtained after the measurements at the end of each stroke.

Figure 8. The measurament setup in the CMM.

3. Results and discussion

3.1. Hardness tests

The results of the macro and micro hardness tests are shown in Figure 9. The hardness results show that the cryogenic treatment (CT) increased the macro and micro hardness of the materials by 1.15 HRC and 2.6 HRC, respectively. Many researchers have studied the impact of CT on the importance of hardness in the enhancement of wear resistance [17, 18, 22, 35-37]. The improvement of mechanical properties depends on the microstructure change and the soaking time. The optimum soaking time was observed as 36 h for the AISI D3 tool steel, and the deep cryogenic treatment eliminated retained austenite and increased the carbide percentage. The cryogenic heat treatment created a more homogeneous carbide distribution with more uniform particle size in addition to forming a number of new nano-sized carbides. The microstructural improvements increased the hardness and microhardness of the deep cryogenically treated samples [5, 26, 32, 33]. The hardness increases during the soaking time due to the increase in martensite transformation in the steel during long soaking periods [19, 37]. The increase in bulk hardness of tool steels with deep cryogenic treatment has been reported earlier in the literature [22, 24, 26, 29, 37, 38].

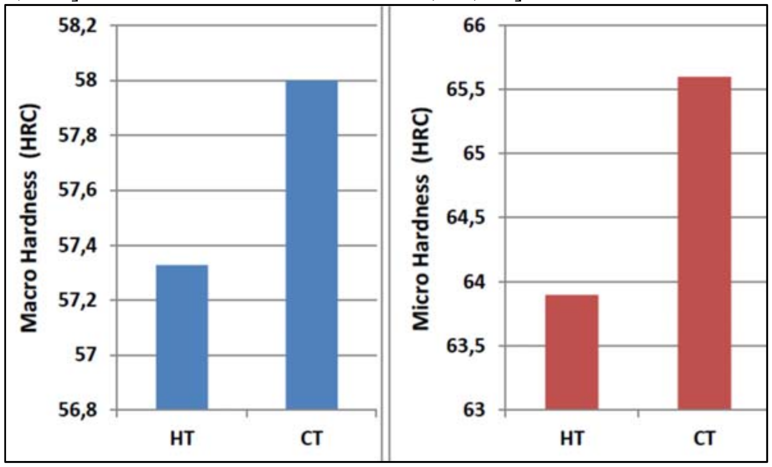
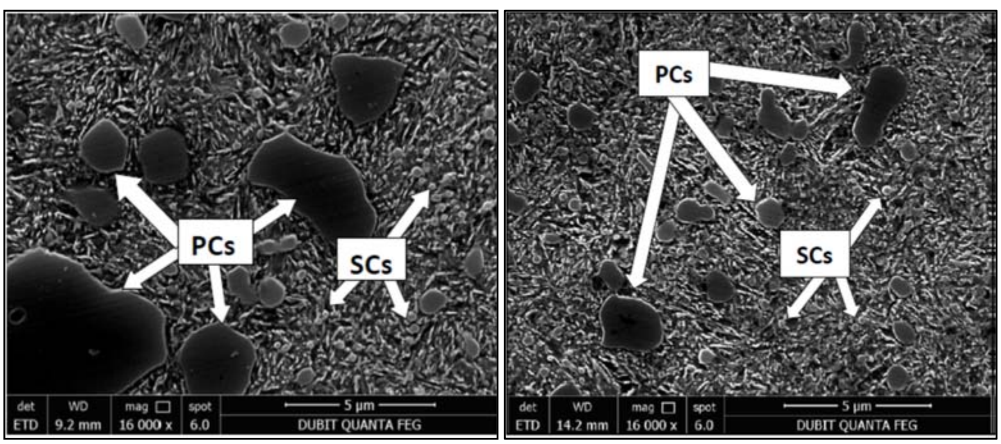


Figure 9. Macro and micro hardness test results.

Cryogenic treatment may result in increased conversion of the retained austenite into martensite and fine carbide precipitation. Additionally, it is well known that the decrease of grain size improves hardness [19,25]. The results obtained in this work as can be seen in Figure 9 confirm the findings in the literature.

3.2.Microstructural analysis

Microstructural investigation was carried out to investigate the changes influencing the enhancement of the properties of the AISI D3 tool steel material when the punches were subjected to cryogenic treatment. The microstructures of the AISI D3 HT and CT samples are shown in Figure 10a and b.



(a) Conventionally heat treated(HT) [5] (b) Cryogenically treated (CT)

Figure 10. Microstructure of AISI D3 samples, SEM-16.000x.

As can be seen, primary carbides (PCs) and secondary carbides (SCs) were distributed quite uniformly and smooth on the martensitic matrix of HT in Figure 10a. The amount, size and distribution of these carbides appear to be affected by the type of heat treatment. Cryogenic treatment significantly reduces the particle size and causes for the better uniform distribution of PC and SC particles in Figure 10b [5]. Das et al. [38] reported that cryogenic treatments refine secondary carbides in particular, increase their amount and population density, and lead to their more uniform distribution in the microstructure. Also, cryogenic treatments did not alter the nature of the primary and secondary carbides. These thoughts have also been reported in prior studies [20-38]. It can be concluded that the cryogenic treatment facilitated the formation of carbide and an increase in the carbide population and its volume fraction in the martensitic matrix of the AISI D3 tool steels. At the same time, it made the carbide distribution more homogeneous (Fig. 10a and b) [25].

3.3. Punch wear analysis

Perforation was performed with a blanking speed of 160 strokes/min in the 25-ton punch machine. Specimens punched were manufactured in dry conditions and at the fixed cutting clearance of 12% of the sheet thickness. Punch wear was evaluated from the weight loss which was obtained as the wear weight loss (mg) per unit area (mm²). Figure 11 shows the relationship between the perforation number and the weight loss for the 5 mm diameter punch (a), the 6 mm diameter punch (b) and the 7 mm diameter punch (c).

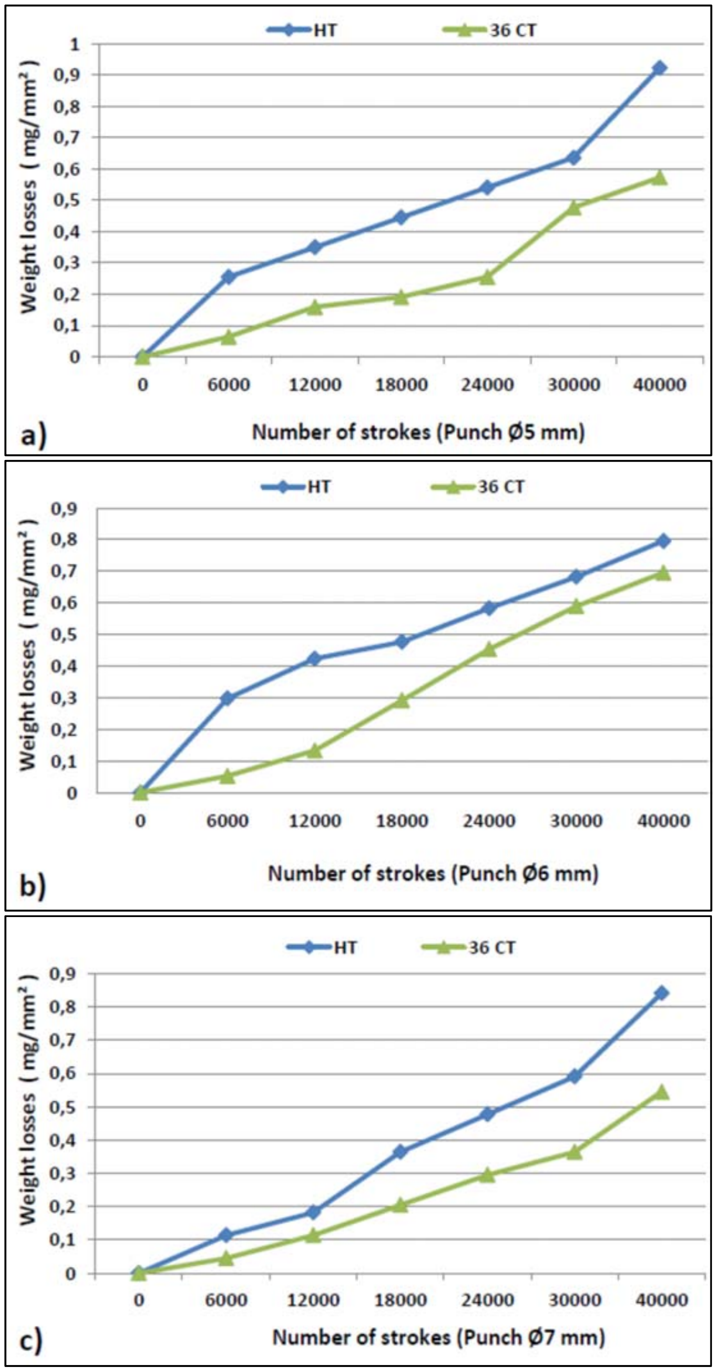
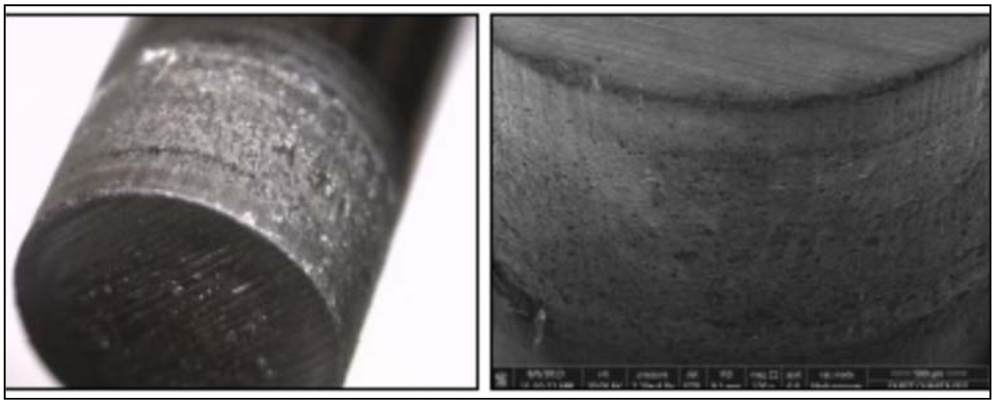
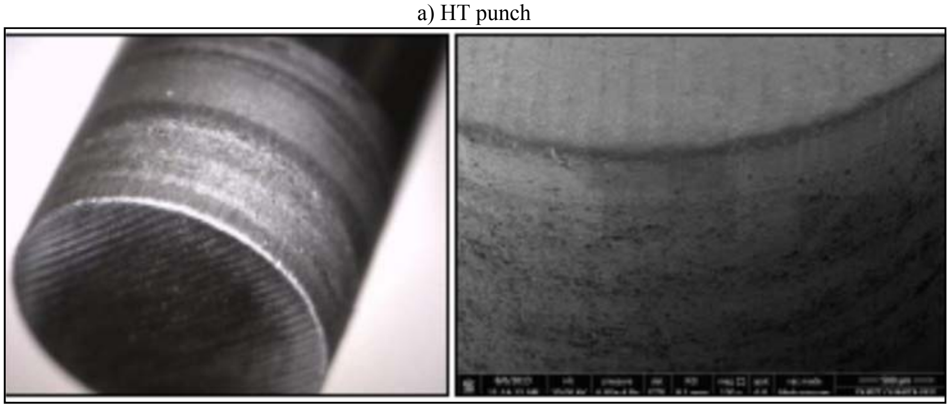


Figure 11. The relationship between weight loss and number of perforation: a) 5 mm diameter punch; b) 6 mm diameter punch; c) 7 mm diameter punch

As shown in Figure 11a, b and c, the wear weight loss after piercing of the 5, 6 and 7 mm diameter punches was respectively 38%, 13% and 35% more in the HT punches compared to the CT punches. These results indicated that the cryogenic process had increased the wear resistance in compliance with the literature [17-20, 24, 25, 29-31, 36]. The OM and SEM images of the HT and CT punch cutting surfaces were used to examine the wear behaviour. Adhesion and abrasive wear were observed on the cutting surfaces of the HT punches (Fig. 12).



a) HT punch



b) CT punch

Figure 12. Face wear of the punch (7 mm-diameter) after 40,000 strokes, OM-50x, SEM-120x [5].

Some researchers reported that, as in many wear studies, the chemical components of the punch and workpiece material have an important role in the formation of the adhesive wear in high chromium materials. Nevertheless, both adhesion and abrasive wear were observed to be less in CT punches. Also, the wear of the cut edge surfaces was seen to be more regular when compared with HT punches [2, 5, 11].

3.4. Measurement of the hole analysis

The hole diameter and circularty error values were measured using in the CMM each cycle. Their average values were obtained after the measurements at the end of each stroke. The CMM values of the hole geometries of the perforated parts were used in this study to evaluate the part quality by examining the hole diameter and circularty. The hole diameter and circularity deviations was obtained from the measured values. These deviations are shown in Figures 13, 14.

As shown in Figure 13, the hole diameter deviation after piercing of the 5, 6 and 7 mm diameter hole was respectively 22%, 17% and 30% more in the HT piercing compared to the CT piercing. Furthermore as shown in Figure 14, the circularity deviation after piercing of the 5, 6 and 7 mm diameter hole was respectively 43%, 12% and 29% more in the HT piercing compared to the CT piercing.

The results showed that the cryogenic process had increased the wear resistance in compatible with the literatüre [17-20, 24, 25, 29-31, 36].

Most punch work processed on overload is broken or quickly eroded. Wear impairs the geometry of the punch and a geometrically-deteriorated punch creates high tribological loads in the sheet metal punching process. Therefore, the hole geometry is affected negatively. The important factor in the hole quality of the piercing is the hole diameter and circularty [2, 5, 6-13].

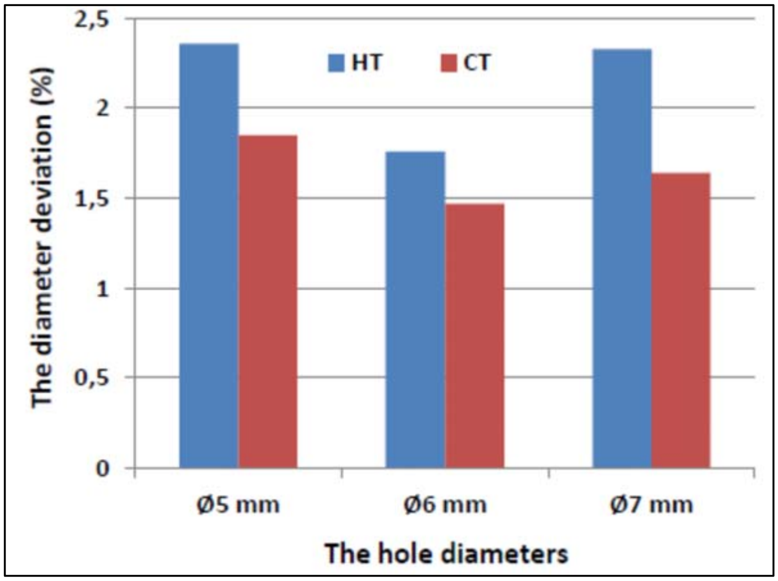


Figure 13. The hole diameter deviation.

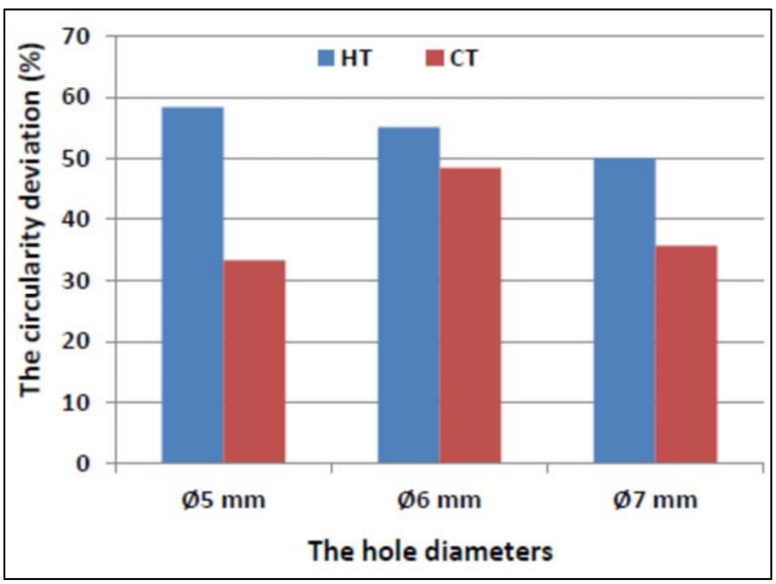


Figure 14. The circularity deviation.

4. Conclusion

In this study, the effect of the deep cryogenic process for 36 h on the wear resistance of the AISI D3 cold work tool steel punch and its impacts on the workpiece hole quality were determined in the piercing process of the AISI 304 stainless steel material. The following results were found:

1. Compared to the traditional heat treatment, the deep cryogenic process increased the macro and microhardness of the AISI D3 cold work tool steel by 0.7 and 1.7 HRC, respectively. The microstructural improvements increased the hardness and microhardness of the deep cryogenically treated samples. By converting the retained austenite to martensite, the cryogenic process reduced carbide size significantly and made distribution of carbides more regular.

2. As a result of the effects of the deep cryogenic process, the wear resistance of the AISI D3 cold work tool steel punches was increased. The wear weight loss after piercing of the 5, 6 and 7 mm diameter punches was respectively 38%, 13% and 35% more in the HT punches compared to the CT punches. These results indicated that the deep cryogenic process had increased the wear resistance.
3. In the SEM and OM images, both adhesion and abrasive wears were observed to be less in CT punches. Also, the wear of the cuting edge surfaces was seen to be more regular when compared with HT punches.
4. The CT punches with increased wear resistance influenced the hole quality of the produced parts. The hole diameter deviation values after piercing of the 5, 6 and 7 mm diameter hole was respectively 22%, 17% and 30% more in the HT piercing compared to the CT piercing. Also, the circularity deviation values after piercing of the 5, 6 and 7 mm diameter hole was respectively 43%, 12% and 29% more in the HT piercing compared to the CT piercing. The deep cryogenic process applied to the punches was proved to increase the punch wear performance. Also, it increased the part quality by having a positive effect on the hole quality of the AISI 304 austenite stainless steel workpieces. Results showed that the deep cryogenic process increased the wear performance of the punches and decreased the value of diameter and circularity variation the hole quality.

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