Canadian Metallurgical Quarterly
The Canadian Journal of Metallurgy and Materials Science

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/ycmq20

Failure analysis of punches and investigation notch impact strength of tool steel cryogenic treated with tempering used in hot forging

Gokhan Atay, Hakan Coşkun & Yusuf Kaynak

To cite this article: Gokhan Atay, Hakan Coşkun & Yusuf Kaynak (07 Nov 2023): Failure analysis of punches and investigation notch impact strength of tool steel cryogenic treated with tempering used in hot forging, Canadian Metallurgical Quarterly, DOI: 10.1080/00084433.2023.2277981

To link to this article: https://doi.org/10.1080/00084433.2023.2277981

CANADIAN METALLURGICAL QUARTERLY
https://doi.org/10.1080/00084433.2023.2277981

Failure analysis of punches and investigation notch impact strength of tool steel cryogenic treated with tempering used in hot forging

Gokhan Atay [a], Hakan Coşkun[a] and Yusuf Kaynak[b]

[a]Torun Metal Inc., GOSB, İhsan Dede St. Gebze, Kocaeli, Turkey; [b]Department of Mechanical Engineering, Marmara University, Istanbul, Turkey

ABSTRACT
Plumbing systems, valves, fittings, condensers, pipes, and other hot-forming components are produced using hot forging, a type of plastic deformation. This method may result in equipment damage due to dies operating under high-temperature conditions, punches breaking, and other issues. The short life of the dies used in forging operations is a longstanding problem for the mass production. To increase the life of die steels, there are continuing attempts to increase the toughness, including heat treatments. In this study, both cryogenic and heat treatments were applied to Dievar,DIN-1.2367 hot work tool steels. The resulting samples obtained were examined in terms of their high temperature and room temperature impact resistance. Observations have shown that operating temperatures significantly affect the impact strength of the material. The study also revealed the direct relation between punch life in mass prodcution condition and tougness. Macroscopic and microscopic examinations were used to examine the crack structures carefully.

Les systèmes de plomberie, les vannes, les piles, les raccords, les condenseurs, les tuyaux et autres composants formés à chaud sont produits par forgeage à chaud, qui est une forme de déformation plastique. Cette méthode peut endommager l'équipement en raison du fonctionnement des matrices dans des conditions de température élevée, de la rupture des poinçons et d'autres problèmes. La courte durée de vie des matrices utilisées dans les opérations de forgeage est un problème de longue date pour le secteur de la production de masse. Afin d'augmenter la durée de vie des aciers pour matrices, des essais sont en cours pour augmenter la résilience, incluant des traitements thermiques. Dans le cadre de l'étude en cours, on a appliqué des traitements cryogéniques et thermiques aux aciers à outils pour travail à chaud Dievar et DIN 1.2367. On a examiné les échantillons obtenus en termes de leur résistance aux chocs à haute température et à la température de la pièce. Les observations ont montré que les températures de fonctionnement affectent de manière importante la résistance aux chocs du matériau. Les résultats de la section expérimentale ont révélé que la durée de vie des poinçons produits dans des conditions de production de masse est également reliée directement à la résilience. On a utilisé des examens macroscopiques et microscopiques pour examiner avec soin les structures des fissures.

ARTICLE HISTORY
Received 16 June 2023
Accepted 23 October 2023

KEYWORDS
Failure analysis; microstructure; hot forging; punch; brass alloy; cryogenic treatment

1. Introduction

Forging process is one of the widely used plastic deformation methods in terms of shaping the material. In this method, in which components from copper alloys are widely produced, the deformability of the billet material increases by heating it in the furnace, and it is easily shaped [1]. Hot work tool steels are materials that are widely used in mass production and frequently preferred in operations that are exposed to high temperatures and mechanical loads during application [2–4]. The working life of hot work tool steels, which also play an important role in the manufacturing industry, is generally dependent on good toughness and high wear resistance [5,6]. As hot work tool steels work at high temperatures, they are subject to tempering action. In this case, plastic deformation and wear occur in processes such as forging due to the decrease in the hardness of the material [2]. Some heat treatments applied to hot work tool steels can enhance their mechanical properties. Controlling the hardness values, microstructural properties and phase distribution of materials by heat treatment is a method used in mass production [5,6]. Heat treatments are highly effective on the impact strength. In addition, tempering temperatures, which are a heat treatment parameter, are an important variable used in changing material properties. Tempering temperatures have been shown to change residual austenite ratios in hot work

CONTACT Gokhan Atay gokhanatay94@gmail.com, gokhanatay@torunmetal.com 41400 Gebze - Kocaeli, TURKEY

tool steels and are a method used to change material properties [7]. Residual austenite ratios directly affect the wear resistance and toughness values of materials. Therefore, it is possible to obtain sufficient hardness and high strength by controlling the tempering temperatures. There are cryogenic process studies in the literature related to this subject [8,9]. Furthermore, the positive effect of cryogenic treatment on material toughness has been demonstrated in studies [8,10]. Leskovsek et al. [11] have investigated the H11 tool steel and the effect of its tempering temperature on the hardness-toughness behaviour of this steel. There are some studies in the literature examining the effect of tempering temperature on wear resistance and toughness. In these studies, wear resistance was tested at different ambient temperatures [12,13]. Acknowledging the continuing discussion about the exact mechanisms behind the positive effects of cryogenic treatment on material properties is essential. Several theories have been proposed, including the transformation of retained austenite into martensite and the precipitation of submicroscopic carbides [14]. While these aforementioned works offer valuable insights, there is a lack of a clear-cut understanding of how cryogenic treatment improves performance. Nonetheless, the importance of reviewing and furthering our comprehension of the effects of cryogenic treatment on steel performance in various applications cannot be overstated. However, there is no systematic study in which the toughness values of cryogenically treated materials are tested at high temperatures. The impact resistance of hot work tool steel materials at high temperatures is of great importance, and therefore, this study aims to address this aspect.

In this study, cryogenic treatment was applied to Dievar and DIN 1.2367 hot work tool steel. Hardness values at 50 HRC after impact strength values of the materials at high temperatures were extensively investigated and compared with the test results performed at room temperature. This study shows a direct relationship in between toughness results and punch lifetimes in mass production conditions.

2. Experimental setup

The forging punch studied in this paper is presented in Figure 1(a). The designed die and the movement of punches in this die is shown in Figure 1(b). A total of six punches in the lower die move forward and backward axially in the punch grooves.

Dievar and DIN 1.2367 hot work tool steel materials were used to fabricate punches used in this study. The chemical compositions of these materials are presented in Table 1. It is seen that Si, C, and Mo element ratios are the main elements that reveal the change in materials. As the ratios of Si and C compounds decrease, the toughness of the material increases. With the increase of particles formed by Si and C elements, more crack formation may occur [14,15]. Different heat treatment parameters were applied to the Dievar and DIN 1.2367 hot work tool steel used in the study. Heat treatment methods of samples with different tempering temperatures are presented in Table 2. Cryogenic treatment was applied to all samples at a temperature of −100°C and for 1 h.

In a Hydromec-550 tons automated press, forging tests were performed. While the experiments were being done, the speed of forging was 6 strokes/min and the process was carried out discontinuously. The experimental setup of the forging process is presented in Figure 2.

The dimensions of the samples for notch impact tests were manufactured in accordance with ASTM E23 standard (10 × 10 × 55 mm with a 45° V notch in the centre) [17]. Notch impact tests were performed on the Hardway impact tester. The experimental setup of the notch impact test is presented in Figure 3 and experimental parameters are presented in Table 3. During impact tests at high temperatures, Optris brand thermal camera was used and temperature values were checked.

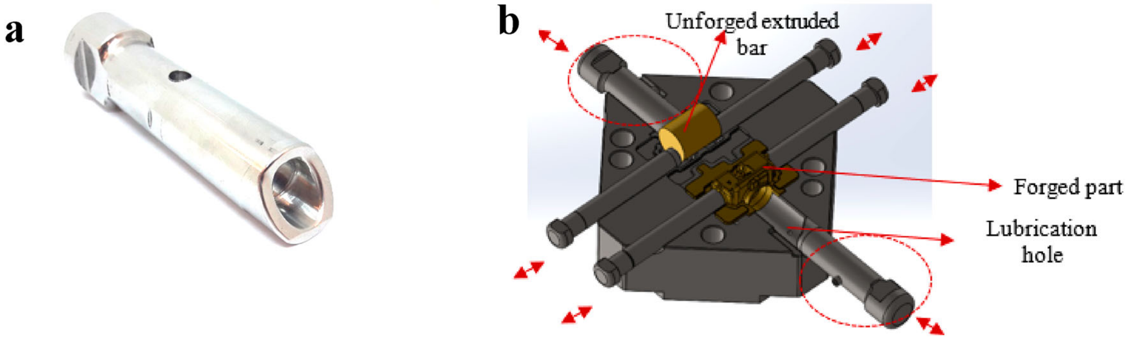

Figure 1. (a) Forging Punch used in this study (b) Punch movements and workpiece in the lower die.

Table 1. Chemical composition of the hot work steels materials used.

Material	C	Si	Mn	Cr	Mo	V
DIN 1.2367	0.38	0.4	0.45	5	3	0.5
Dievar	0.35	0.2	0.5	5	2.3	0.6

3. Results and discussions

3.1. Visual inspection

The damaged punch causes some deformations in the brass piece over time. Images of these damages are presented in Figure 4. The hardness value of the punch material, microstructure examinations and fracture surface examination were completed and the reasons that could lead to breakage were examined. First, the damaged samples were visually inspected.

The damage mechanisms of the punch material are presented in Figure 5. It has been observed that the piece of brass material deforms and damages the punch tip form over time. In the life follow-ups, it was determined that the crack initiation of this punch started after producing an average of 800–1000 pieces.

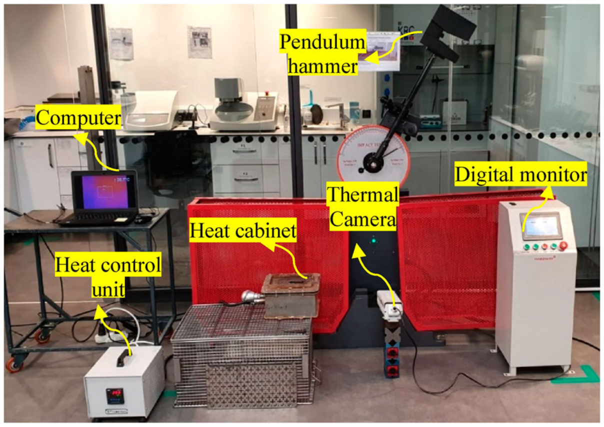

Figure 3. Experimental setup of Charpy-V test.

Figure 6 shows the section in which microstructure images showing crack propagation of the damaged forged punch material are taken.

3.2. Microstructural examinations

In order to see the crack propagation mechanism in more detail, the microstructure and crack propagation

Table 2. Heat treatment parameters applied to DIN 1.2367 and Dievar material.

Material/treatment type	Hardening	Cryogenic	1. Tempering	2. Tempering	HRC ±1
DIN 1.2367-HT	1050°C, 3 bar, 2 fan	–	570°C, 3 h	600°C, 4.5 h	50
DIN 1.2367-CT	1050°C, 3 bar, 2 fan	−100°C, 1 h	570°C, 3 h	600°C, 4.5 h	50
Dievar-HT	1020°C, 3 bar, 2 fan	–	570°C, 3 h	560°C, 4 h	50
Dievar-CT	1020°C, 3 bar, 2 fan	−100°C, 1 h	570°C, 3 h	560°C, 4 h	50

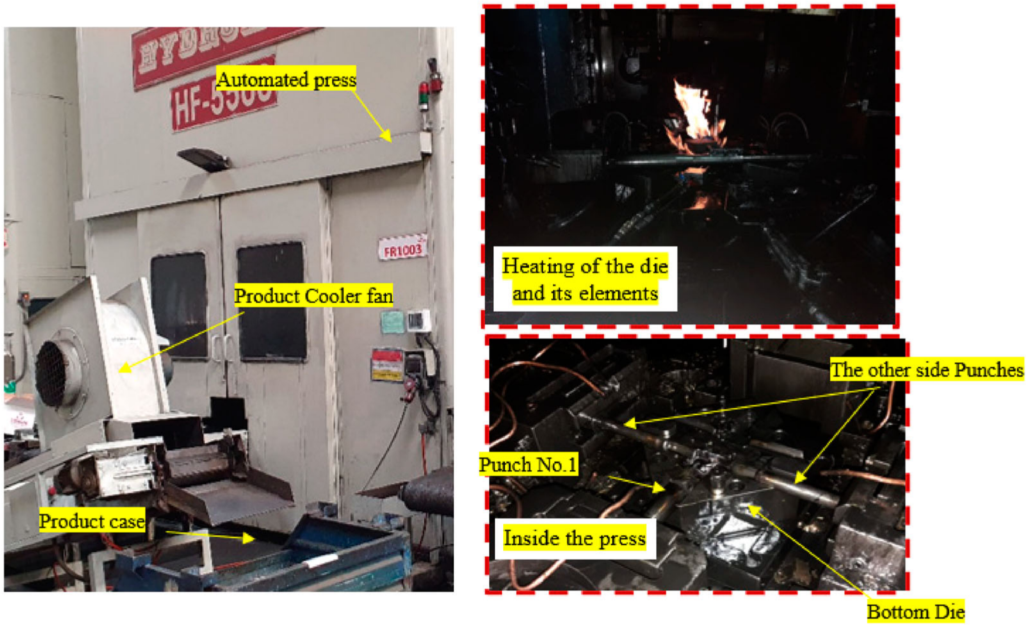

Figure 2. Forging press and experimental setup.

Table 3. Experimental parameters.

Material	Treatment type	Notch impact test material temperature
DIN 1.2367	Cryogenic Treatment (CT)	RT
DIEVAR	Heat Treatment (HT)	300°C

of the punch material presented in Figure 7(a) were examined. It is an obvious that the deformation of the material is caused by parts of the brass material that break off from the workpiece. After a certain forging cycle, the brass workpiece deforms the punch materials, revealing fracture and deformation damage mechanisms.

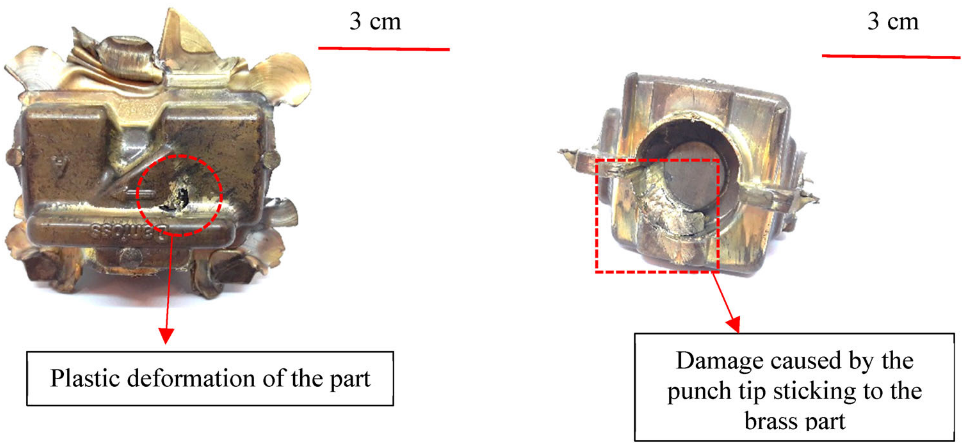

Figure 4. Brass component formed by hot forging using the punch.

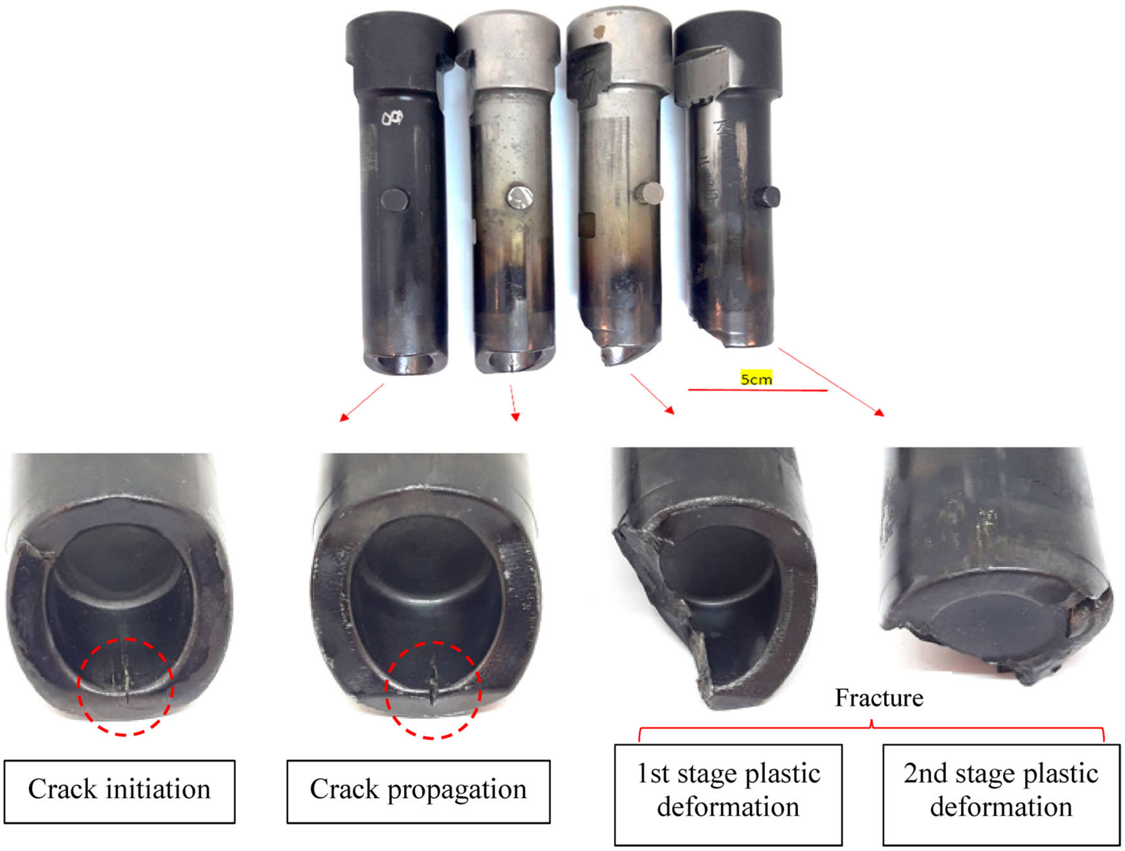

Figure 5. Damage and crack propagation mechanisms in punch.

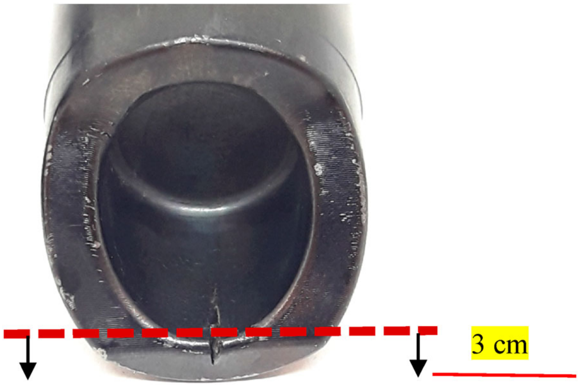

Figure 6. Illustration of the section taken for microstructure studies of damaged forging punch material.

Our observations have shown that after a certain number of cycles, the brass material adhering to the punch materials during hot forging deforms the form punch tips, leading to the formation of a crack mechanism and subsequent damage. When the microstructure images of the damaged punch are examined, the deformation of the punch material is affected by the pieces of the brass material broken off from the workpiece. Brass workpiece exposed to high compressive stresses along with high forging temperature deforms the punch materials over time, revealing fracture and deformation damage mechanisms.

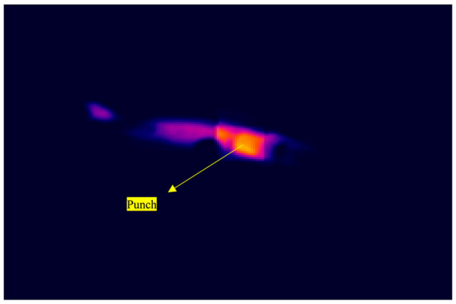

Figure 8. Punch temperature measured by thermal camera.

3.3. Toughness

Notch impact samples were manufactured for all heat treatment conditions performed within the scope of the work. Three pieces were produced from each sample and the experiments were repeated three times and averaged. Serial manufacturing conditions were investigated in relation to breakage damages in the punches. First, preliminary studies were carried out to determine the operating temperatures of the punches. The punch temperatures measured by the thermal camera during the forging process are in the range of 300–350°C on average (Figure 8). Therefore, the experiments for the hot notch test were carried out at 300°C.

Impact strength values calculated after notch impact tests are presented in Figure 9 depending on material, treatment type and notch temperature. As can be seen from the figure, cryogenic treatment and ambient temperature have an effect on the impact strength of the material. Impact strength in notch samples with a hardness of 50 HRC for DIN 1.2367 material and tested under room temperature conditions was calculated as nearly 14 J on average. With the ambient temperature at 300°C, the impact resistance increased by 128.5% to about 32 J. It was observed that the impact energy values increased with the increase in temperature. This increase is caused by the transformation of ductile pits in the structure as the temperature increases. The impact strength of the heat-treated Dievar material notch specimens tested at room temperature was calculated as 45 J on average. At an ambient temperature of

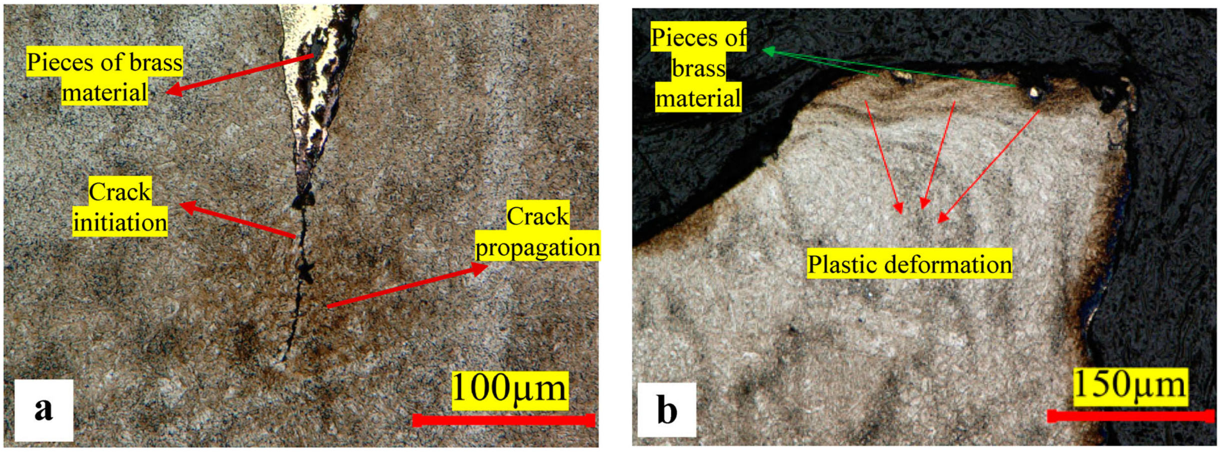

Figure 7. (a) Damage and crack propagation mechanisms in punch, (b) Sub-surface plastic deformation image that occurred in the punch.

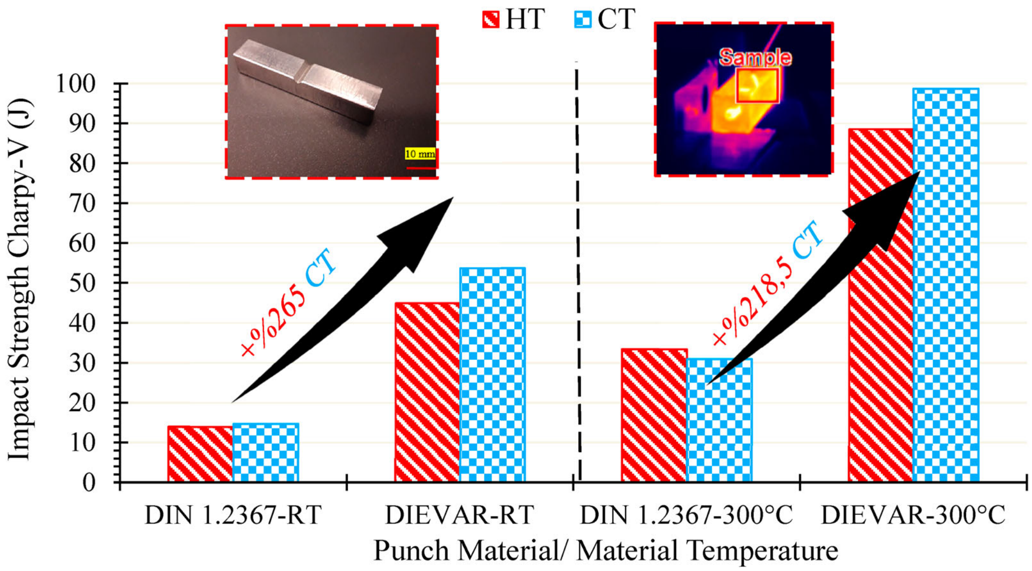

Figure 9. The effect of changes in temperature and tempering type on toughness values in different materials as a result of V-notch impact tests (The hardness value for all samples is 50 HRC).

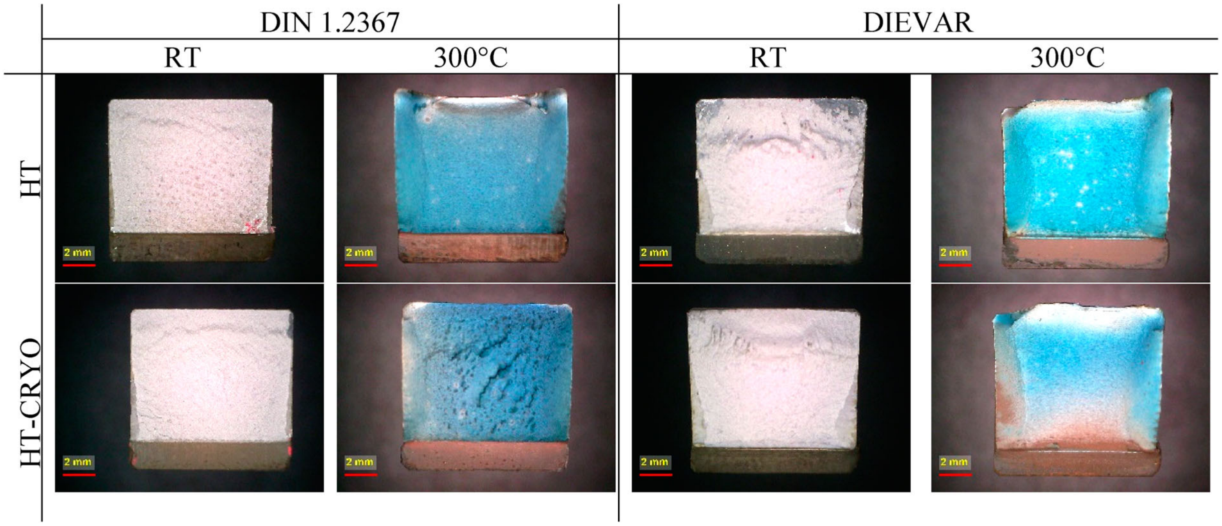

Figure 10. Fracture surface images after notch impact test at RT and 300°C.

300°C, the impact resistance increased by 97% to approximately 88.5 J. For the cryogenically treated Dievar material notch specimens tested at room temperature was calculated as 53.65 J on average. At an ambient temperature of 300°C, the impact resistance increased by 84% to approximately 98.7 J. Nucleation, growth and coalescence of pits in the structure at elevated temperatures are the main ductile fracture properties [14–16]. On the other hand, heat treatment and cryogenic treatment for DIN 1.2367 materials showed similar effects and closer toughness results. In Dievar material, the effect of cryogenic treatment is evident, including tests at room temperature and 300°C temperature condition. Cryogenic treatment increased the impact strength by 19% compared to heat treatment in tests performed at room temperature. In the 300°C temperature condition, 11.5% change occurred. In general, the major effect was seen by changing the material. Dievar material, which has been cryogenically treated at ambient conditions, has 265% higher impact strength than DIN 1.2367 material. In the ambient temperature of 300°C, this change was 218.5%.

Fracture surface images formed after notch impact tests at different material, treatment type and different ambient temperatures was presented in Figure 10.

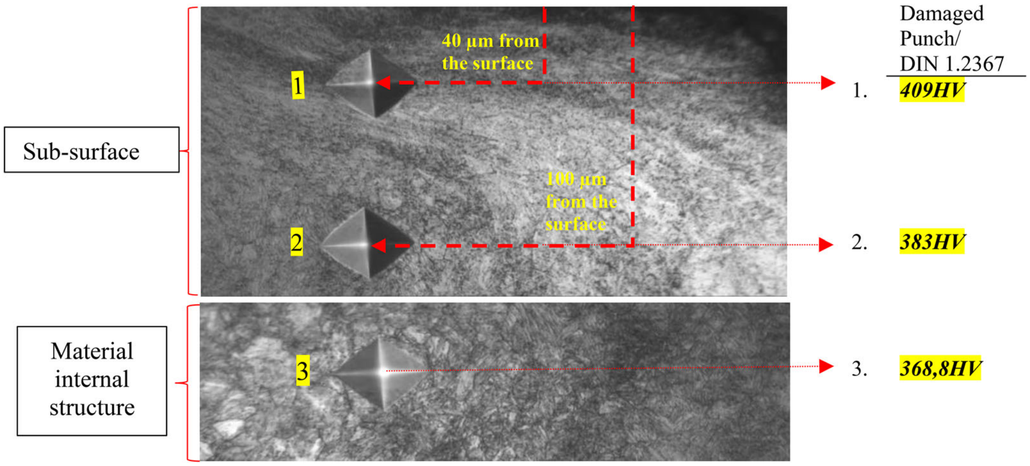

Figure 11. Hardness measurement sample image of the damaged punch and microhardness value of punch.

3.4. Microhardness

The damaged punch material's subsurface and in-material hardness measurements and values are shown in Figure 11.

As seen from the values presented in the table, there is an increase in hardness due to strain hardening near the subsurface. The change in microhardness was considered as another finding related to the damage of the punch subjected to variable loads. In addition, the punches in contact with the brass material undergo plastic deformation and break after a certain number of cycles as a result of the broken brass pieces sticking to the punches.

3.5. Tool life control

In the light of this theoretical information obtained, four punches were produced from the Dievar material, which underwent both heat treatment and cryogenic treatment and their lifetimes were followed under mass production conditions.

As can be seen in Figure 12, the average tool life, which is produced from DIN 1.2367 heat-treated material currently in use, was around 1000 pieces at the beginning, while the life of the punch in which the same heat treatment was applied in Dievar material increased to approximately 1800 pieces per punch with an increase of 78%. In the punch where the

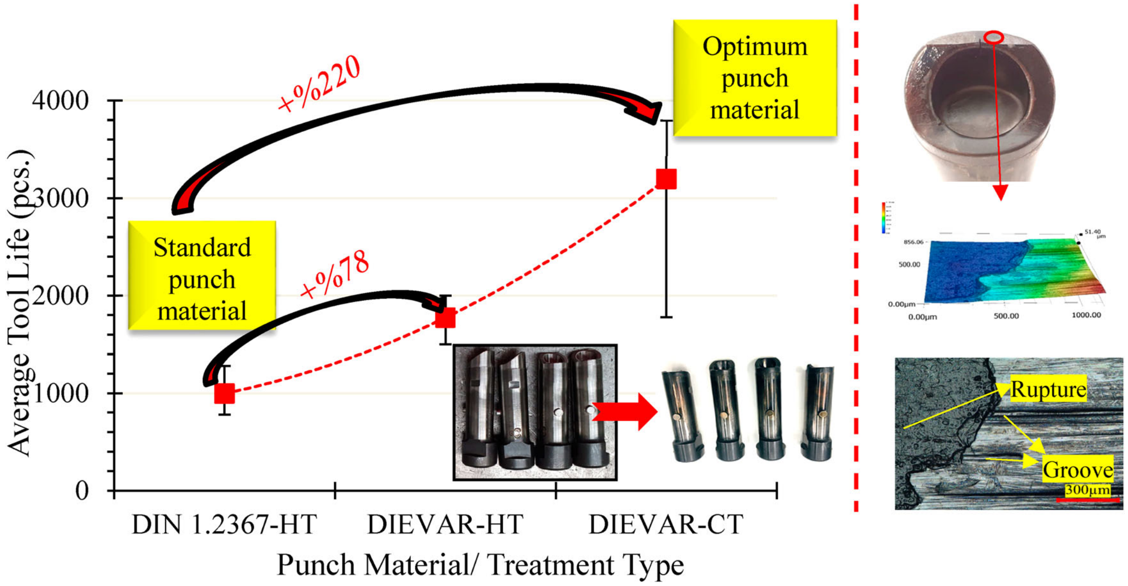

Figure 12. Effect of the punch material and treatment type on the average tool life of the punches under mass production conditions.

cryogenic treatment was applied, the tool life increased by 220% and became around 3200 pieces.

4. Conclusion

In this study, comprehensive investigations were carried out on the plastic deformation and fracture mechanism of the punches, which are one of the die elements used in mass production.

The study has revealed a direct correlation in between punch failure and toughness. This relationship was established through experiments conducted at both room conditions (approximately 25°C) and at elevated temperature, 300°C, which represent the operational conditions of the punch during hot forging process of brass alloy. It has been demonstrated that there is a significant increase in toughness values in the heat-treated and cryogenic-treated samples of Dievar material compared to the DIN 1.2367 material currently in use. This increase has been shown to be strongly related to the lifetime of the punches used under mass production conditions, with an average an approximately 220% increase in punch lifetime.

Disclosure statement

No potential conflict of interest was reported by the author(s).

ORCID

Gokhan Atay http://orcid.org/0009-0006-0270-3676

References

[1] Francis R. The corrosion of copper and its alloys: a practical guide for engineers) NACE International ; 2010. p. 5–176.

[2] Barrau O, Boher C, Gras RB, et al. Analysis of the friction and wear behaviour of hot work tool steel for forging. Wear. 2003;255(7–12):1444–1454. doi:10.1016/S0043-1648(03)00280-1

[3] Boher C, Le Roux S, Penazzi L, et al. Experimental investigation of the tribological behavior and wear mechanisms of tool steel grades in hot stamping of a high-strength boron steel. Wear. 2012;294:286–295. doi:10.1016/j.wear.2012.07.001

[4] Wei MX, Wang F, Wang SQ, et al. Comparative research on the elevated-temperature wear resistance of a cast hot-working die steel. Mater Des. 2009;30(9):3608–3614. doi:10.1016/j.matdes.2009.02.023

[5] Zhang C, Li P, Wei S, et al. Effect of tempering temperature on impact wear behavior of $30Cr_3Mo_2WNi$ hot-working die steel. Front. Mater. 2019;6:149. doi:10.3389/fmats.2019.00149

[6] Zhu Z. Property data collection of common hot working die steels used in China. Mech Eng Mater. 2001;24:38–42.

[7] Cao Y, Wang Z, Kang J, et al. Effects of tempering temperature and Mo/Ni on microstructures and properties of lath martensitic wear-resistant steels. J Iron Steel Res Int. 2013;20(4):70–75. doi:10.1016/S1006-706X(13)60085-0

[8] Koneshlou M, Asl KM, Khomamizadeh F. Effect of cryogenic treatment on microstructure, mechanical and wear behaviors of AISI H13 hot work tool steel. Cryogenics. 2011;51(1):55–61. doi:10.1016/j.cryogenics.2010.11.001

[9] Çiçek A, Kara F, Kıvak T, et al. Effects of deep cryogenic treatment on the wear resistance and mechanical properties of AISI H13 hot-work tool steel. J Mater Eng Perform. 2015;24:4431–4439. doi:10.1007/s11665-015-1712-x

[10] Pérez M, Belzunce FJ. The effect of deep cryogenic treatments on the mechanical properties of an AISI H13 steel. Mater Sci Eng A. 2015;624:32–40. doi:10.1016/j.msea.2014.11.051

[11] Leskovšek V, Šuštaršič B, Jutriša G. The influence of austenitizing and tempering temperature on the hardness and fracture toughness of hot-worked H11 tool steel. J Mater Process Technol. 2006;178(1–3):328–334. doi:10.1016/j.jmatprotec.2006.04.016

[12] Wei MX, Wang SQ, Wang L, et al. Effect of tempering conditions on wear resistance in various wear mechanisms of H13 steel. Tribol Int. 2011;44(7–8):898–905. doi:10.1016/j.triboint.2011.03.005

[13] Alam MT, Arif S, Ansari AH. Wear behaviour and morphology of stir cast aluminium/SiC nanocomposites. Mater Res Express. 2018;5(4):045008. doi:10.1088/2053-1591/aab7b3

[14] Handbook AM. Heat treatment. New York: American Society for Metals; 1991; Vol. 4, p. 367–413.

[15] Alam MT, Ansari AH, Arif S, et al. Mechanical properties and morphology of aluminium metal matrix nanocomposites-stir cast products. Adv Mater Process Technol. 2017;3(4):600–615.

[16] Tanwir Alam M. Physical, corrosion and microstructural analysis of A356/SiC nanocomposites fabricated through stir casting process. Mater Sci Forum. 2021;1034:73–86. doi:10.4028/www.scientific.net/MSF.1034.73

[17] American Society for Testing and Materials. ASTM standard test methods for notched bar impact testing of metallic materials: E 23-12c. ASTM, 2012.