



Article

Experimental Investigation of Die Performance in Cold Forging Backward Extrusion

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Abstract

Cold forging backward extrusion is mainly employed in the manufacturing of axisymmetric cup-like components used extensively in automotive and aerospace assemblies due to the process-induced strength that has a pivotal role in such applications. Although cold forging backward extrusion yields mechanically robust components, it demands high forces, subjecting tooling to immense stress, thereby restricting process capacity. The process encounters hindrances in gaining widespread industrial acceptance due to frequent failures of die elements, necessitating proper die design and control of major influencing factors for process viability and cost-effectiveness. The punches in backward extrusion are often susceptible to failures when processing steel billets. The punch service life is significantly affected by geometrical attributes, the type of steel undergoing deformation, and tool manufacturing aspects. Hence, the present study evaluates punch performance in cold forging backward extrusion using optimized geometrical attributes, manufactured through a design of an experimental approach comprising an L9 orthogonal array. The manufacturing factors considered are punch material, hardness, and advanced surface coating. Punches were designed for two industrial components using powder metallurgy (PM) steels—S600, S290, and S590, heat treated to 60–66 HRC, and coated via physical vapor deposition with TiN, AlTiN, and TiAlCN. Punch performance was analyzed against existing industry practices, and the strategy demonstrated improved productivity. Punch performance was determined based on the number of forgings produced before wear- and fatigue-induced failures. Significant improvements in punch performance were witnessed in both high-speed steel (HSS) and PM punches with optimized geometries. Fractographic investigations were carried out on fractured punches and analyzed, focusing on the coating's effect on the thermal aspects of the punches. The proposed study will assist the cold-forging industry in determining appropriate variables to minimize forming responses, thereby enhancing tool life. The research also benefits industries by enhancing process robustness and improving process efficiency with respect to cost and time.



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Keywords: cold forging backward extrusion; die performance; punch fatigue and wear performance; powder metallurgy-based steels; fractographic investigations

1. Introduction

Cold forging involves large forces to deform the metal, leading to frequent die failures. Hence, when using steel as a billet material, die performance is a major issue that limits the economic viability of the process [1]. Die performance in cold forging depends on various influencing factors; the forming behavior of steel is the most significant among other factors, such as tool hardness, coatings, lubricants, deformation rates, etc. [2]. Die elements have to sustain a huge amount of stress during the cold forging of steel parts; in particular, punches used for the backward extrusion process are more prone to failure since, in addition to deformation loads, frictional stresses come into play as metal flows upward past the punch, as illustrated in Figure 1.

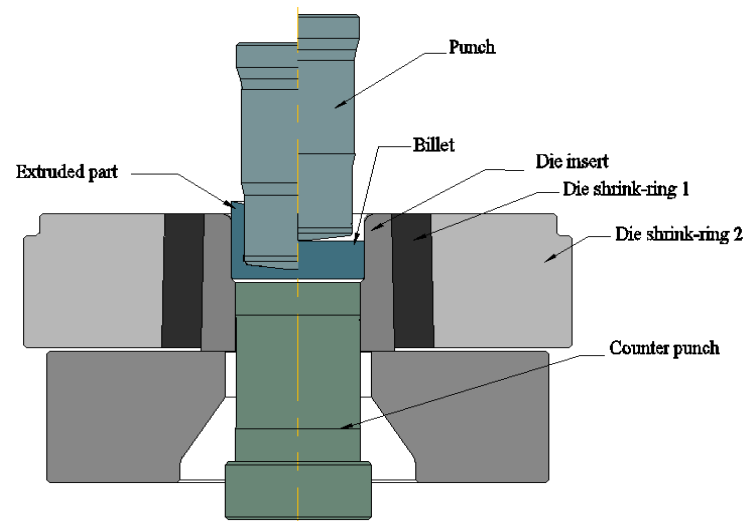


Figure 1. Cold forging backward extrusion process.

In backward extrusion, the shape of the punch must be given close attention to facilitate metal flow, but most of the time, it is governed by the internal profile of the final component. The forming behavior of steel governs the geometrical aspects of the punch necessary to improve the punch's overall service life [3,4]. The elastic behavior of the punch and die affects the accuracy of the part being forged [5]. Chen et al. [6] studied component errors caused by die elements' elasticity, secondary yielding, spring back, and temperature during cold forging. Appropriate preform design efficiently achieves component accuracy while minimizing the forming loads and die pressures [7]. Statistical techniques, along with finite element (FE) simulation tools, are now becoming popular and widely employed in the design of dies. The established methodology helps to analyze stress distribution in the punch and die and improves the process of obtaining tighter tolerances in manufacturing precision automotive parts like gears, sleeve cams, etc. [5,8]. Appropriate selection of die materials is imperative to achieve good die life at a reasonable cost. Fatigue and wear are the two crucial failure mechanisms for cold forging dies; consequently, any improvement in these properties increases die life [9].

The fatigue behavior of the punch depends on the type of steel, the heat treatment procedure, and the hardness of the punch/die [10]. Since the material properties can be expressed in terms of hardness, it is possible to set up guidelines for predicting the fatigue life of cold forging dies based on theoretical models [11]. Investigations on the nature of high- and low-cycle fatigue behavior of tooling in cold forging were carried out to evaluate the influence of material and hardness factors concerning lifetime calculations using numerical techniques and were validated with experimental tests. Based on experience, AISI M2 HSS has been found to be the most satisfactory material for general use, having a good combination of wear resistance, fatigue strength, compressive strength, hot hardness, and resistance to tempering

during service [12]. However, the AISI M42 type of HSS material has excellent compressive strength and has been used successfully for highly stressed punches where greater hardness is necessary than what is possible with AISI M2, AISI D2, or AISI D3 steels. The steels AISI M2, AISI D2, and D3 are usually employed for short-run applications because of their low cost and relative ease of heat treatment, but their use is not recommended because of low fatigue strength, poor shock resistance, and lack of hot hardness [13,14]. It is evident that in conventional tool steels (AISI D2, D3, H11, H13) and high-speed steels (AISI M2, M3, and M42), fractures occur without any noticeable plastic deformation because of the higher percentage of carbon and the transformation into carbides after heat treatment. The stress level necessary for causing fracture basically depends on the size and location of the initial defect, as can be perceived from a fracture-mechanics point of view. To substantiate, such defects are primarily large carbide clusters or non-metallic inclusions [15–17]. The harmful effects of these carbide clusters and inclusions may be overcome by the powder metallurgical (PM) processing route. Over the last decade, the PM tool steel sector has focused on minimizing inclusions as the main threat to die life in cold forging operations. The uniformity of properties is another favorable effect of PM processing as opposed to conventionally produced ingot material. Segregation during solidification and the shape of the ingot create inhomogeneous structures and properties in the conventional processing of tool steels [18,19].

Another major issue associated with the cold forging process is friction and wear. This puts a high demand on developing lubrication systems and die coatings to improve tribological aspects [20]. Tooling surfaces must withstand high loads and promote uniform metal flow at contact regions during deformation [21]. On the other hand, the billet is usually coated with lubricant layers such as zinc phosphate and molybdenum disulfide to sustain large plastic strains [22]. Many investigations have been made to precisely analyze the mechanical properties at the tool–workpiece interface; friction and wear phenomena were studied using experimental/numerical couplings [23]. There are many friction measurement methods that have been devised. These tests are basically formulated by following cold forging practices such as upsetting, ring compression, and forward and backward extrusion that result in the determination of friction behavior models with various values of friction coefficients based on the contact conditions between the tooling and the billet interface [24–27]. Gariety et al. [28] evaluated new lubricants, such as MEC Homet, Daido Aqualub, and MCI Z-coata, as alternatives to zinc phosphate pre-coating with a double-cup backward extrusion tribo-test. Recently, Medea et al. [29] researched the friction behavior of new environment-friendly solid lubricants with due attention to die temperatures while forging aluminum (AA1050) cans for the cosmetic industry. A double-layer type environment-friendly lubricant was tested by Sagisaka [30], and in a practical application, this lubricant type showed performance similar to that of a conversion coating lubricant. The degradation of tool surfaces by wear can be minimized with hard coatings, and in one such study carried out by Dubar et al. [31], improved die life was observed in the production of screws; the dies, which were made of AISI M2, were analyzed for wear when PVD and CVD TiN-coated.

The factors affecting the die performance can be grouped under design, manufacturing, and in-process categories. The design phase includes the material and geometrical aspects of the punch and billet (shape, size, and preform) affecting the overall forming behavior of steel in cold forging. The manufacturing phase is confined to factors such as billet preparation, heat treatment, and surface coatings to improve tribological properties, while the in-process phase includes press conditions, deformation velocities, lubricants, and thermal effects. It would be difficult to evaluate the performance of the die/punch considering these various factors. However, the present research makes an effort to include the most significant parameters that affect overall production performance of punches. Therefore, research on die performance in cold forging initially started with evaluating the

forming behavior of different AISI grades of steel commonly employed for manufacturing automotive parts through ANN-based process modeling. The factors considered to evaluate AISI steel forming behavior are billet size ratio (z), reduction ratio (r), punch angle (α —deg) and land height (h —mm). The billet size ratio (BSR), is determined as the ratio of the billet's length (L_0) to its diameter (D_0), and the ratio of reduction (RR) is the ratio of the difference in the cross-sectional area of the billet (A_0) and the punch (A_1) to the billet's cross-sectional area, as denoted by Equations (1) and (2):

$$\text{Billet Size Ratio, } z = \frac{L_0}{D_0} \quad (1)$$

$$\text{Reduction Ratio, } r = \frac{A_0 - A_1}{A_1} \quad (2)$$

The differential evolution (DE) optimization technique is utilized to arrive at the best combinations of geometrical attributes influencing the forming responses, such as effective stress ($\sigma_{eff.}$), strain ($\epsilon_{eff.}$), strain rate ($\epsilon_{rate.}$), and punch force (F) of different grades of AISI steel [2,32]. Further, the study is extended to analyze the punch performance of the cold forging backward extrusion process for industrial components, accounting for important manufacturing factors like die materials, heat treatment, and coatings.

2. Experimental Details

2.1. Materials and Methodology

The punches in cold forging backward extrusion are manufactured traditionally with conventional high-speed steel (HSS) such as AISI M2 and M42, which are expected to sustain stresses up to 1800–2200 MPa [12]. Recent developments in the field of advanced die materials makes use of the powder metallurgy (PM) route, where punches of PM-HSS are expected to sustain stress levels up to 2500 MPa and advanced die coatings also substantially increase wear resistant capability [33]. Table 1 illustrates the compositions of the Bohler-grade (micro clean) PM-based materials selected for the manufacture of punches for the cold forging backward extrusion process.

Table 1. Chemical composition of PM-based advanced die material (as provided by supplier).

Bohler Material	Avg. % Chemical Composition (Inspected)									
	C	Si	Mn	Cr	Mo	Ni	V	W	Cu	Co
S600	0.90 (0.90)	- (0.28)	- (0.29)	4.10 (3.89)	5.00 (4.76)	-	1.80 (1.72)	6.20 (5.98)	-	- (0.68)
S290	2.0 (1.98)	0.5 (0.41)	0.3 (0.24)	3.8 (3.63)	2.5 (2.36)	-	5.1 (5.12)	14.3 (14.12)	-	11.0 (10.93)
S590	1.29 (1.30)	0.6 (0.61)	0.30 (0.30)	4.20 (3.93)	5.00 (4.95)	- (0.26)	3.00 (3.03)	6.30 (6.21)	- (0.10)	8.4 (8.22)

In the current investigation, the effort is focused on quantifying punch performance by considering manufacturing factors such as die materials, hardness and coatings. In cold forging, coating effectiveness depends on functional properties beyond hardness. Reduced friction lowers interfacial shear stress and forming load, while improved resistance to adhesive and abrasive wear and galling delays tool degradation. High thermal stability and strong coating–substrate adhesion under cyclic compressive stresses are essential for extending punch life and improving forging performance. Tables 2 and 3 illustrate combinations of this significant punch manufacturing factors, utilizing an L_9 orthogonal

array devised based on the design of experiments (DoE). The Bohler-grade PM materials are S600, S290 and S590, which are micro-cleaned and recommended for cold forging applications [34]. Similarly, the punches are vacuum heat-treated to obtain a hardness in the range of 60–66 HRC and are further finished-machined to achieve close dimensional tolerances and better surface finish. An advanced physical vapor deposition (PVD) coating is employed for punches to obtain desired wear-resistant properties. The advanced PVD coatings for punches are TiN (designated as A), AlTiN (designated as B) and TiAlCN (designated as C), as recommended by Bohler for cold forging applications [35].

Table 2. Control factors for punch manufacturing.

Level	Punch Material	Hardness (Rockwell C-Scale)	Designation—Coating Type
I	S600	60–62	A-TiN
II	S290	62–64	B-AlTiN
III	S590	64–66	C-TiAlCN

Table 3. Combinations of factors for punch manufacturing.

Code on Punch	Punch Material	Hardness (Rockwell C-Scale)	Coating Type
S6-1	S600	60–62	A
S6-2		62–64	B
S6-3		64–66	C
S2-1	S290	60–62	B
S2-2		62–64	C
S2-3		64–66	A
S5-1	S590	60–62	C
S5-2		62–64	A
S5-3		64–66	B

There are nine combinations of punches manufactured as per L9 orthogonal array-experimental design. Considering the optimal geometrical aspects and effect of type of material, coatings and hardness level will be analyzed. The punch performance can be estimated by number of forgings produced before the punch fails due to wear or fatigue.

2.2. Manufacturing of Punches

2.2.1. Design of Punches

The punches are designed by considering the configuration of the final geometry of the part and a feasible geometry for the cold forging backward extrusion process. However, the analysis is carried out based on the experimental strategy illustrated in Table 4 for both cases 1 and 2. The punches were manufactured with conventional high-speed steel M42 for the experimental strategy “only with optimal geometrical attributes”, whereas the punches with the experimental strategy “Geometrical attributes + Manufacturing variables” are manufactured as per the schedule mentioned in Tables 2 and 3 with Bohler-grade advanced PM-based die materials.

The component of case 1 can be backward extruded in a single stage with an extruded diameter of $\varnothing 28 \times 49$ mm from a billet size of $\varnothing 36 \times 30$ mm, while the second component of case 2 has to undergo a two-stage backward extrusion process to achieve the final

configuration as depicted in Figure 2 (a and b), respectively. The final configuration of the component with close tolerances has been achieved through finish machining, except for the backward extruded internal spline profile, while the preliminary preform of the part geometry is obtained through cold forging backward extrusion. The finite element simulation was carried out to confirm the feasibility of the process and to decide upon the stage-wise deformations for the second component. The results are depicted in Figure 3.

Table 4. Punch design details with experimental strategy.

Component 1, Case 1, Single-Stage Backward Extrusion						
Punch Description and Material	Billet Material	Billet Size Ratio	Reduction Ratio	Optimal Punch Angle (deg)	Optimal Land Height (mm)	Experimental Strategy
Plain BE HSS (M42)	AISI 1010	0.8	0.4	170	2.5	Only with optimal geometric attributes
Component 2, Case 2, Two-Stage Backward Extrusion						
Plain BE stage I and II Advanced PM-grade material	AISI 1018	1.8	0.6	170	4	Geometric attributes + Manufacturing variables
		1.2	0.6	170	4	
Profiled-BE HSS (M42)		0.5	0.6	160	4	Only with optimal geometric attributes

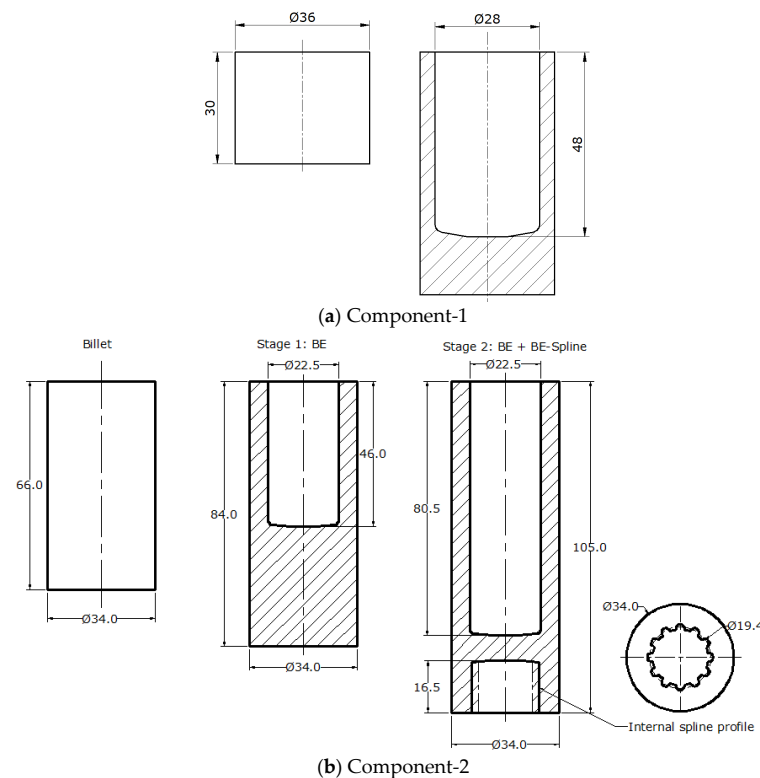
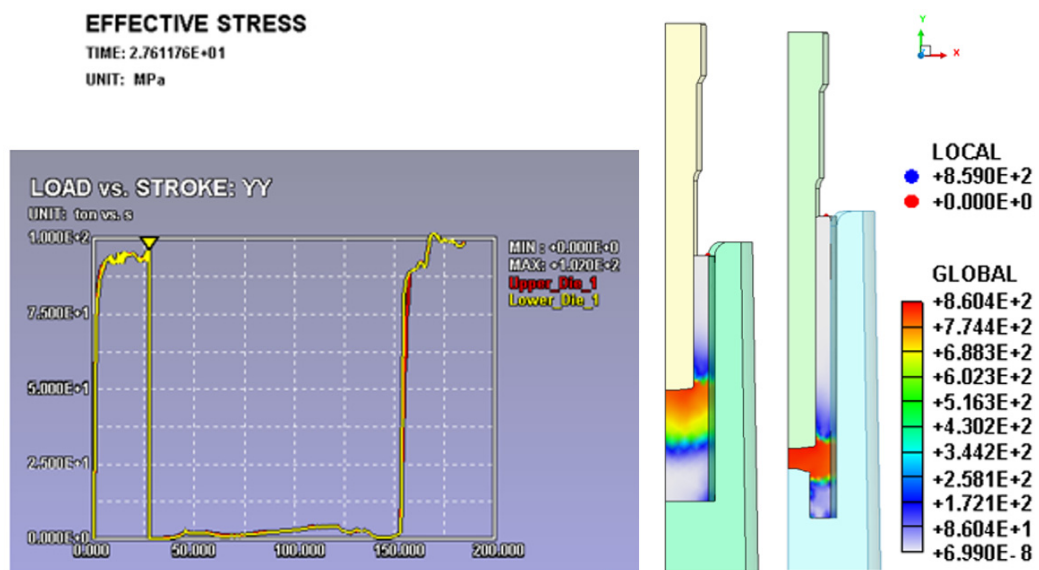
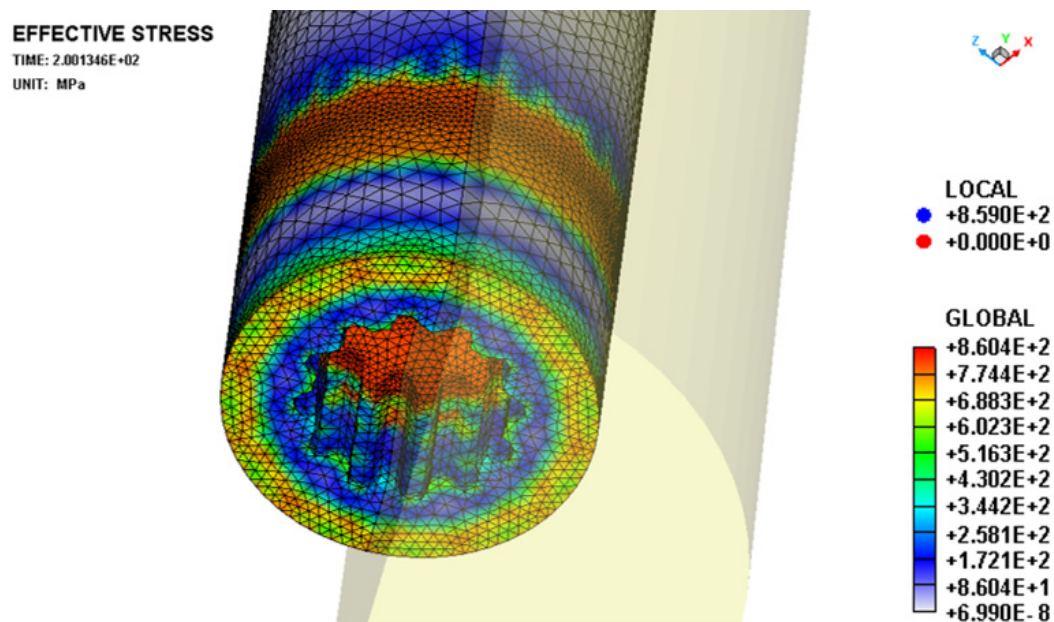


Figure 2. Industry components identified for the research on die performance studies. (a) Component 1: Single-stage backward extrusion—Case 1. (b) Component 2: Two-stage backward extrusion—Case 2.



(a) Effective stress is 859 MPa, and max. punch force is 102 tons.



(b) Rendered 3D-simulated image

Figure 3. FE simulation results for second component—Case 2: (a) effective stress in the billet and max. punch force; (b) rendered 3D FE-simulated images.

Three-dimensional models of the punch, billet, and die were prepared for the two-stage process for the second component and were imported into AFDEX 2004 SPO metal forming simulation software in stereolithographic (.stl) format [36]. The software has an in-built material and friction model library, which was assigned to models accordingly to perform FE simulations. The punches were machined on a CNC turning center as per the requirements mentioned in Table 4, with a finishing allowance, and were sent for the vacuum heat treatment process to achieve desired hardness. Punch hardness of 60–62 HRC is maintained for conventional HSS, whereas, for Bohler-grade material, the hardness was obtained as summarized in Table 3.

The punches for heat treatment are first preheated at 850 °C, and the temperature is raised to about 1050 °C and 1150 °C for the second preheat, followed by austenitizing at 1180 °C. Then, quenching is carried out with N₂ gas at a pressure of 5 bar, and thereafter, the first stage of tempering is done at 550 °C, followed by the second stage at 560 °C. The

third-stage tempering temperatures are varied to obtain different hardness values in the range of 60–66 HRC, and the actual hardness of the punches is confirmed.

2.2.2. Advanced Surface Coatings on Punches

Cold forging die elements usually fail due to wear in larger production runs. To improve wear-resistant properties, punches and dies are surface-coated. Physical vapor deposition (PVD) coatings are preferred over chemical surface coatings [31]. Therefore, in the present study, advanced surface coatings for punches were chosen as one of the important factors among other manufacturing variables. Advanced surface coatings normally preferred for cold forging applications are TiN, AlTiN and TiAlCN, as recommended by Bohler, and accordingly, punches were coated with a thickness of 3–5 μm as reported in Table 5 and shown in Figure 4. The PVD coatings were deposited at the Bohler PVD Coating Facility, Pune, India, operated by voestalpine High Performance Metals India Private Limited, Mumbai, India (voestalpine Group). Coatings were applied using a commercial cathodic arc PVD system (ALPHA 400P PVD COATING SYSTEM, voestalpine eifeler -Vacotec, GmbH, Düsseldorf, Germany). TiN, AlTiN, and TiAlCN coatings with a thickness of 3–5 μm were deposited following Bohler's standard parameters recommended for cold forging tooling. Coating thickness was measured using a ball-crater abrasion tester (Calotest CAT²c, CSM Instruments, Peseux, Switzerland). Coating hardness was evaluated using a micro-Vickers hardness testing system (HVM-2, Shimadzu Corporation, Kyoto, Japan) under low-load conditions to minimize substrate influence. For each coating, measurements were conducted at multiple locations, and the average values are reported in Table 5.

Table 5. Heat treatment schedule for punches manufactured with Bohler-grade material.

Parameter	S6-1, S2-3, S5-2 TiN	S6-2, S2-1, S5-3 AlTiN	S6-3, S2-2, S5-1 TiAlCN
Coating thickness	3.4 μm	3.5 μm	4.5 μm
Coating hardness	2800 HV	3300 HV	3500 HV



Figure 4. PVD-coated punches with the codes marked.

2.3. Experimental Setup

The steel billets were prepared with a standard procedure, which included cropping the bar stock accurately, annealing to bring down the hardness value to well within 130 BHN, cleaning, de-scaling, phosphating and coating with molybdenum disulfide (MoS_2) powder of 3 μm particle size before placing them in the die cavity to facilitate

better deformation [32]. The production of forgings was planned on a 600-ton hydraulic press (CHIMAHO Automation Systems) in accordance with an industry process in Bangalore, as depicted in Figure 5. The force required to deform a billet is very large in the case of the cold forging process, and the optimal geometry of the punch helps to reduce the force required during the process [37]. In the current investigation, force during deformation was captured through a 2500 kN button-type load cell (MONAD Electronics, Jaipur, India 302022) and recorded with a digital single-lens reflex camera (Nikon D5600 DSLR).

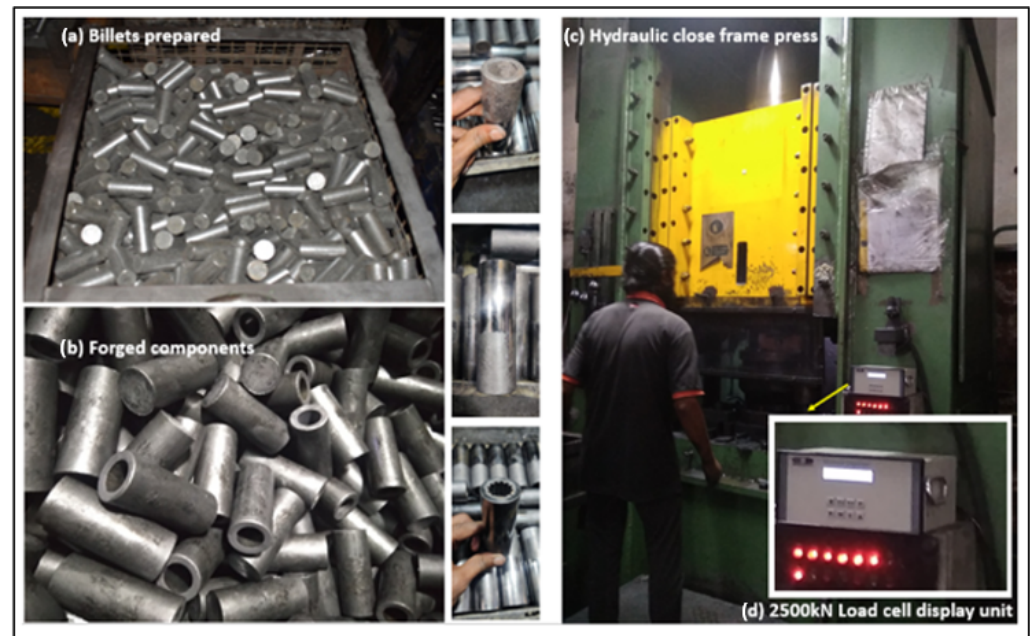


Figure 5. Images of (a) billets prepared; (b) forged components; and (c) close-frame 600-ton hydraulic press attached with (d) 2500 kN force load cell and experimental setup (Courtesy: S. S. Industries, Bangalore, India).

During deformation of the billet in cold forging backward extrusion, the work done is dissipated in the form of heat, and the punch temperature rises stroke by stroke. The temperature drops to ambient during off-production and again starts rising once production starts. The cyclic thermal effect on the structural integrity of the punches was analyzed by acquiring data on the rise in temperature of the punch. Accordingly, the rise in temperature of punches was measured during production with a digital non-contact infrared (IR) thermometer temperature gun (HTC Instrument MTX-2). The production schedules were prepared in compliance with the ongoing experiments. The factory operated for 24 h in three shifts, and 750 forgings could be produced in each shift. The production processes were recorded, and some extra time was allotted for the changeover of the punches or any unforeseen maintenance tasks. The forging cycle time was about 100 strokes/hour, and the rise in the temperature of the punches for every 20 strokes was noted for a lot of 500 strokes/forgings in the production schedule, which approximately accounted for 300 min.

Tribological aspects like friction between contact surfaces, wear and lubrication play an important role in the cold forging backward extrusion process. The punches in backward extrusion not only experience deformation loads but also frictional forces between the billet and punch, as the material flows past and over the descending punch [22,38]. The punch wears excessively in the backward extrusion process; therefore, this was accounted for in the current research by incorporating the effect of advanced coatings on the wear behavior of the punches, thereby improving their performance. The present study also focused on the performance of punch wear in both cases mentioned earlier for two industrial

components involving cold forging backward extrusion. The punches were inspected after every 2000 forgings to quantify the wear, and the maximum wear was deduced, as depicted in Figure 6, using a tool maker's microscope.

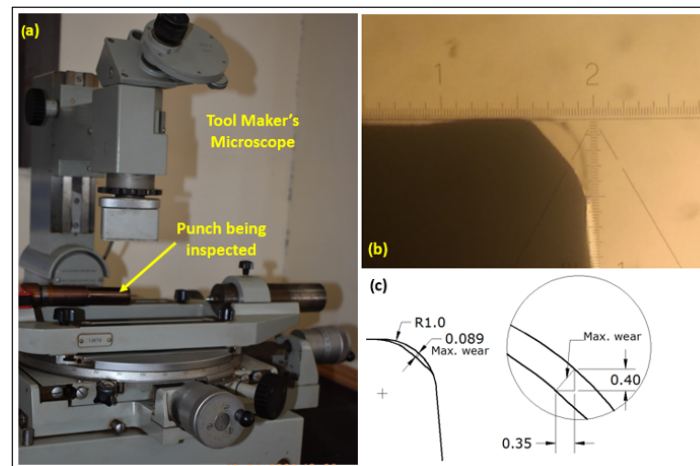


Figure 6. Wear inspection using tool maker's microscope. Images of (a) tool maker's microscope; (b) image from view lens; and (c) wear measurement.

It was also observed that the fillet corner and land on the punch are more susceptible to wear as compared to the rest of the region, as shown in Figure 6b. The maximum wear was obtained by estimating the hypotenuses through measuring the x–y coordinate distance from the goniometer profile set with the tool maker's microscope, as illustrated in Figure 6c.

3. Results and Discussion

3.1. Analysis of Punch Production Performance

The production performance of punches, as summarized in Figures 7–9 for two instances of cold forging backward extrusion of industrial components, indicated an overall improvement.

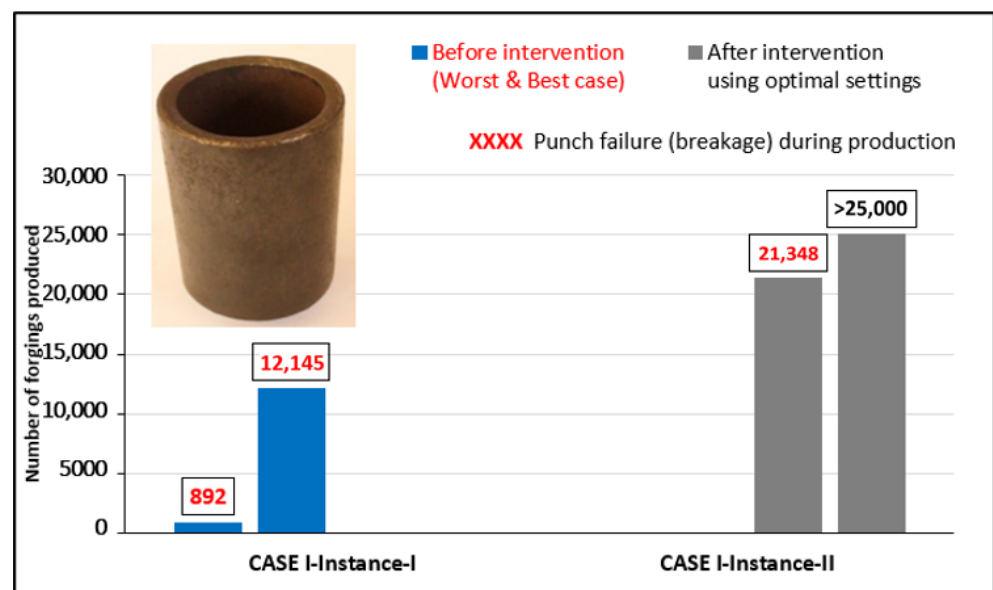


Figure 7. Punch performance for component 1: single-stage plain backward extrusion.

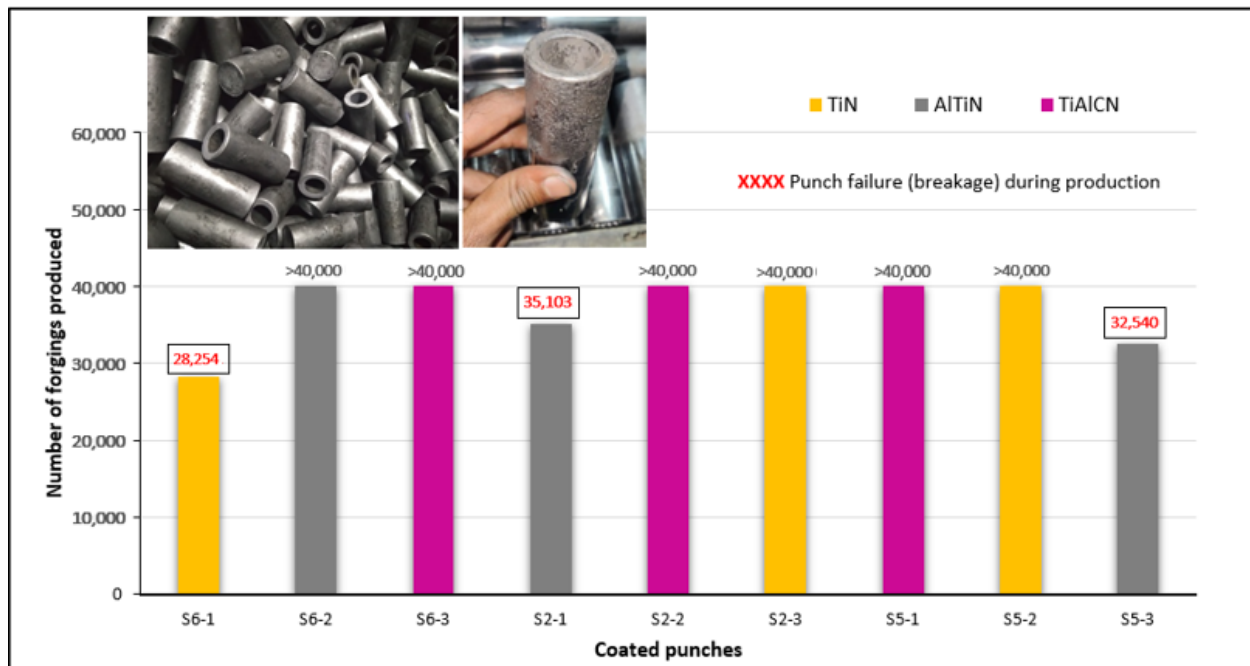


Figure 8. Punch performance for component 2: backward extrusion in stages I and II.

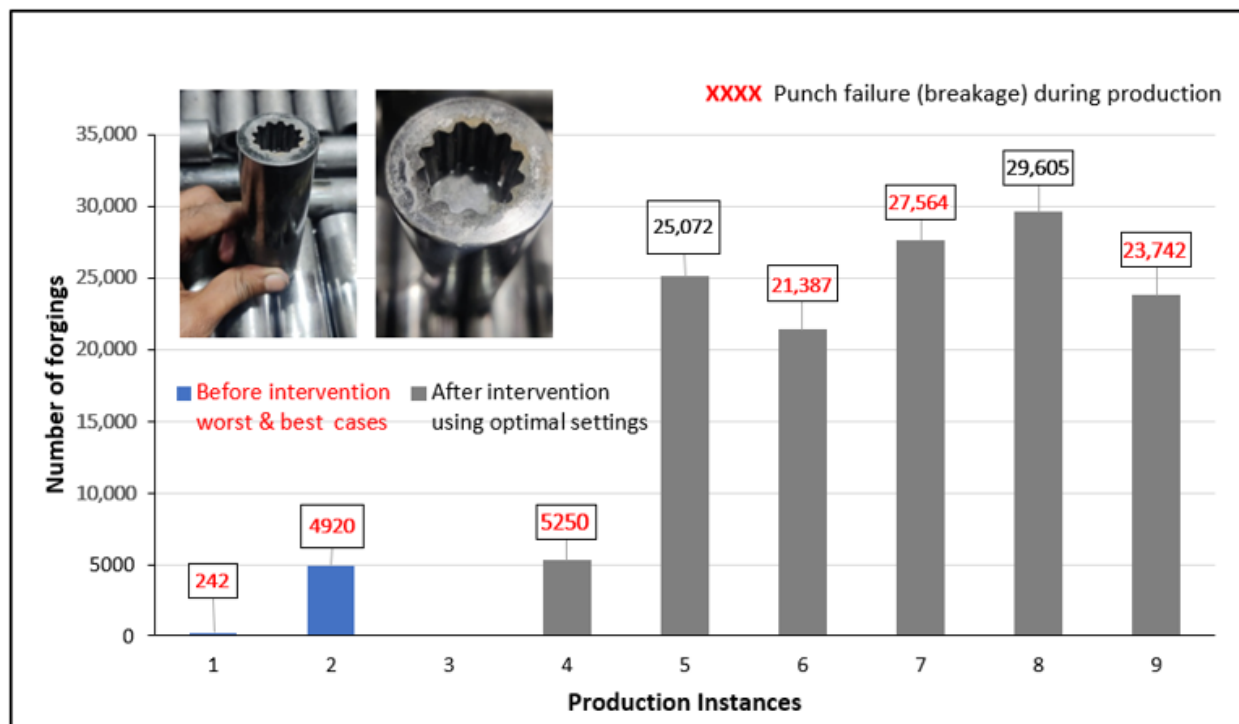


Figure 9. Punch performance for component 2: second-stage spline-profile backward extrusion.

As mentioned in Tables 3 and 4, in case 1 of the first component, punch performance approximately doubled by incorporating optimal geometric attributes for the specified billet size and reduction ratios. The first punch failure (breakage) occurred at the neck region of the hole diameter after production of 21,348 forgings, whereas the subsequent punch operated beyond 25,000 forgings as scheduled for production. This improvement in punch production performance was witnessed for punches designed with optimal geometric attributes based on preliminary investigations on the forming behavior of steel.

The punches with optimal geometric attributes and manufactured with PM-based advanced die materials, different hardness levels, and advanced coatings, evidenced an approximately 40% improvement in production performance compared to the punches of case 1 for the first component. However, three punches failed (breakage occurred) during production, as illustrated in Figure 8.

The overall improvement in punch performance for component 2 was due to advanced coatings that enhanced wear life. Moreover, six punches functioned beyond the production target of 40,000 forgings. The punch (counterpunch) performance in case 2, for component 2, during the second-stage backward extrusion of the spline profile (uncoated), improved threefold over the earlier reported punch life, as depicted in Figure 9.

The punches manufactured with M42 HSS with an optimal punch angle and land height showed wear initiation at 9000 to 15,000 forge operations with tolerable profile deviations. There were two instances of severe punch wear that occurred, during forging of the 25,072nd and 29,605th forged components, making the punches unsuitable for production, as summarized in Figure 9.

The Bohler-grade advanced PM material S600, S290, and S590 punches, illustrated in Table 3 with varying degrees of hardness and advanced coatings, performed 40% better than conventional HSS punches. The production schedule (15,000/month during January 2022 to December 2022) was distributed uniformly among the nine DoE strategy punches. For the second component of case 2, six out of nine punches, each with a set target of 40,000 cycles (for stage I or II) proved satisfactory in operation, with minimum dimensional variability for their further usage.

The production schedule to meet the industry timeline was followed during this research intervention through preliminary investigations (forming aspects) and manufacturing aspects (punch material, hardness and coating) adopted in real-time production detailed in subsequent sections.

3.2. Analysis of Punch Fatigue Performance

The punch material had a bearing on forging quality, and its life deteriorated due to inappropriate design, manufacturing, and forging conditions. The PM-based punch that handled a maximum stress of about 2500 MPa performed better than HSS punches (1800–2200 MPa) [39]. The punch fatigue life considerably increased for optimal geometric attributes of steel forming behavior, as evidenced by Figure 8. However, fractographic images (scanning electron microscope) of optimized HSS punches illustrated in Figure 10 highlighted the presence of brittle cracks that were potential punch failure factors. Microstructural characterization was carried out using a field-emission scanning electron microscope (EVO MA18, Carl Zeiss Microscopy GmbH, Oberkochen, Baden-Württemberg, Germany). SEM observations were performed at the Central Analytical Instrumentation Facility (CAIF), Manipal Academy of Higher Education (MAHE), Manipal, Karnataka, India.

For high-speed steel, a trans-granular structure was observed at the fatigue fracture leading edge surface (Figure 10c,d), that differed from the other cleavage fracture region with micro peaks and valleys (Figure 10c). The stretched zones were clearly visible between the fatigue fracture leading ridge surfaces and other adjacent surfaces, as shown in Figure 10d. There was clear evidence of agreement between these fracture features and the extensive investigations on HSS fatigue fracture by Ebara et al. [40].

The Bohler PM advanced-grade S600, S290, and S590 punches with optimal geometric attributes, as shown in Figure 8, had 40% improved production performance. However, among the nine punches, two failed during production runs due to fatigue, while one failed during press stroke setting, indicating a 66% success rate. The SEM microstructures at 1 μm and 2 μm magnification levels of heat-treated and hardened punch samples, as illustrated

in Figure 11, were prepared with representative punches selected. These punches for component 2, hardened to 60–66 HRC, followed the DoE strategy provided in Table 4.

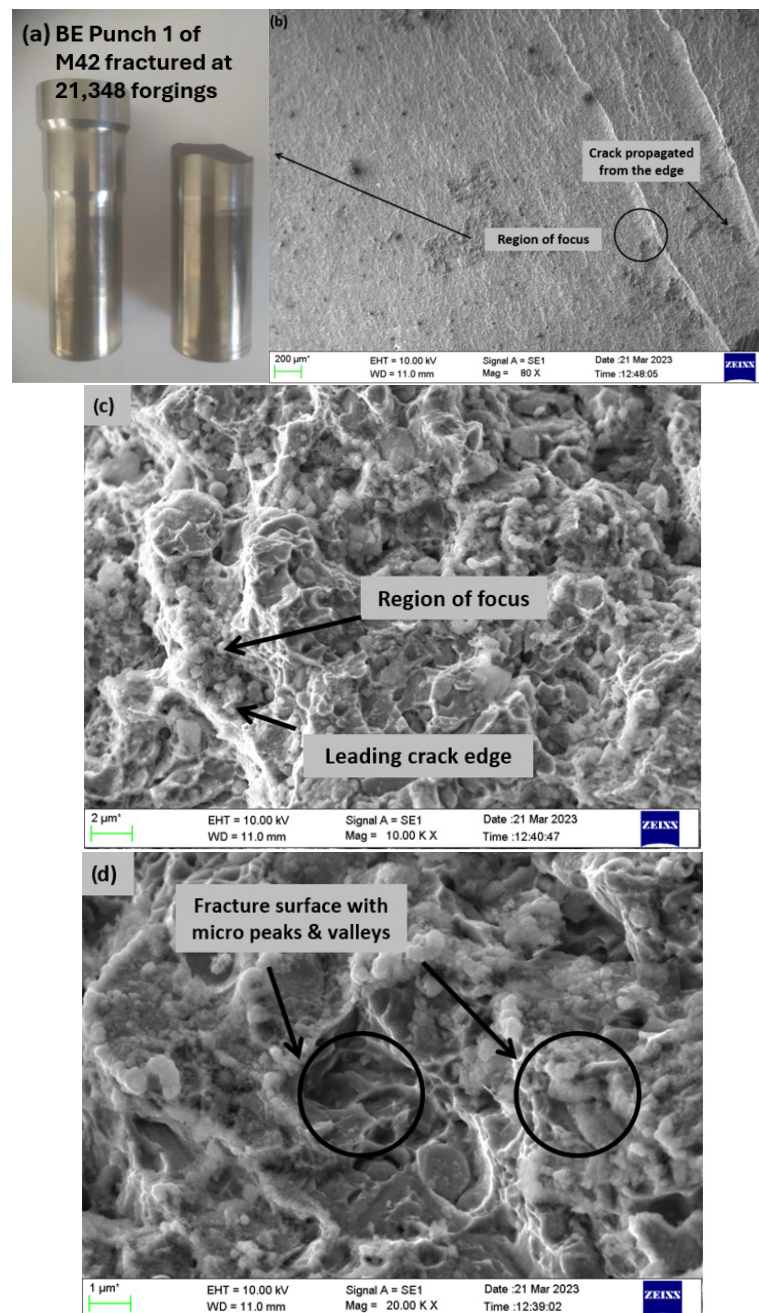


Figure 10. Fracture surface morphology of punch: (a) broken punch, (b) crack region on the fractured surface, (c,d) magnified SEM images at 1 and 2 μm. (Note: The * symbol near the scale bar is part of the original SEM image and does not indicate anything specific).

The metallographic features of S600, S290, and S590 were differentiated by their extent of observed ferrite matrix, eutectic carbides, and granular inclusions of secondary carbides. The microstructure of steel after heat treatment, as shown in Figure 11a–c, indicated the presence of martensite, retained austenite (in small residual amounts), and eutectic carbides that were respectively observed as an acicular structure in original austenite grains, bright grain areas, and bright massive inclusions. The granular inclusions along grain boundaries were secondary carbides [41].

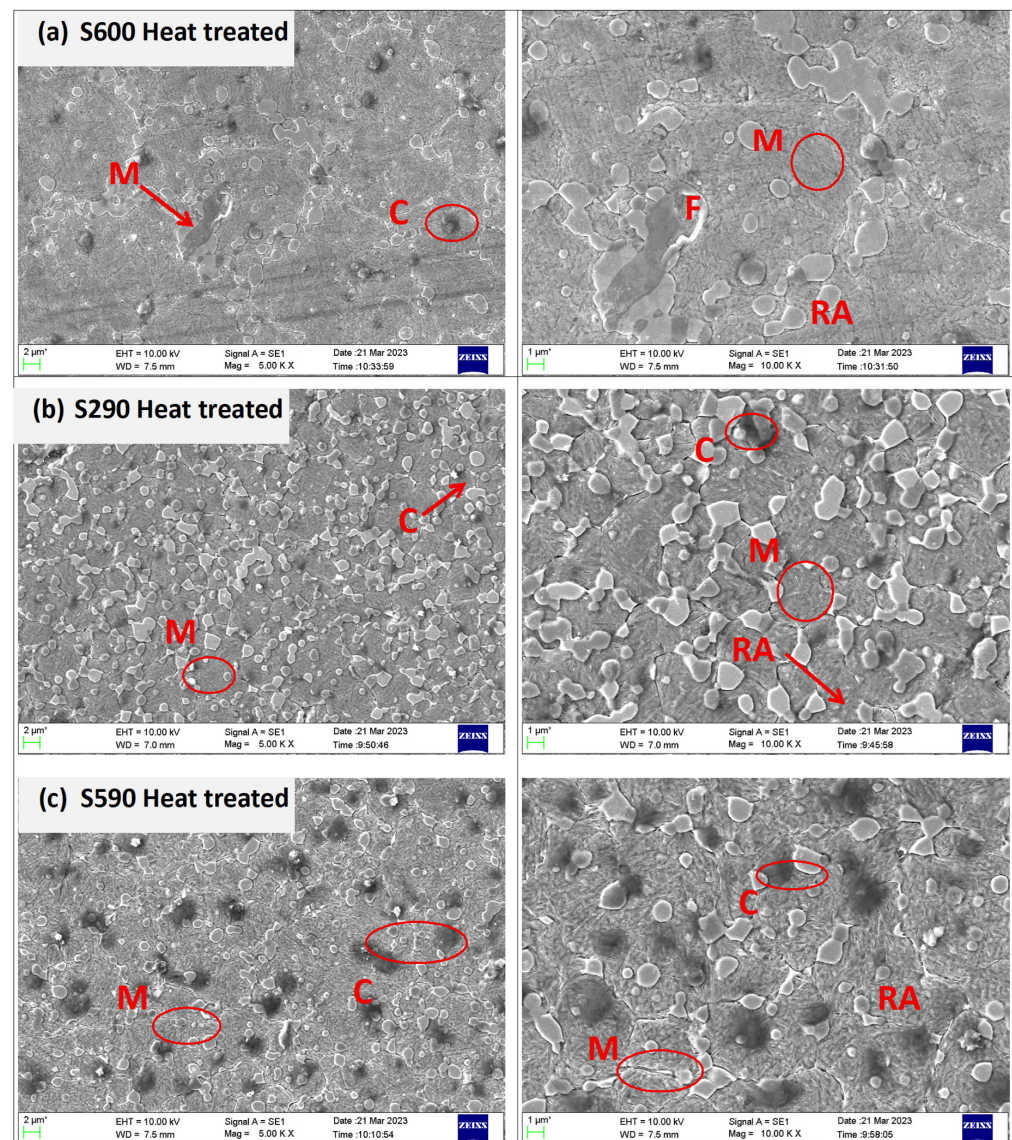


Figure 11. The metallographic structure after heat treatment of PM grades of steel (M: martensite, RA: retained austenite, F: ferrite, and C: carbides) used for punches; (a) S600, (b) S290, (c) S590 with magnified SEM images at 1 and 2 μm . (Note: The * symbol near the scale bar is part of the original SEM image and does not indicate anything specific).

The S6-1 punch for backward extrusion of the second component, stage I, produced 28,254 strokes before fracture of the neck region during press setting for stage II, as indicated in Figure 12.

The SEM images of the propagated neck region crack of the PM punch revealed a very fine brittle fracture microstructure, unlike the HSS fracture surface that had micro peaks and valleys. The punch probably failed due to excessive stress induced by counter-punch thrust during stroke settings. Stage I of backward extrusion of the second component had a sleeve that guided the punch into the die chamber, preventing punch deflection during deformation. However, during the second stage of extrusion, inadequate guided punch motion by the extruded region of the component might have been the reason for its fracture. Macroscopic observation of the fracture surface in Figure 12b,c revealed crack initiation at the neck region, which is susceptible to stress concentration, leading to fracture. A transgranular fracture surface was seen on the crack leading edge from Figure 12d, while cleavage fracture with peaks and valleys was observed on adjacent fracture surfaces of the punch (Figure 12e).

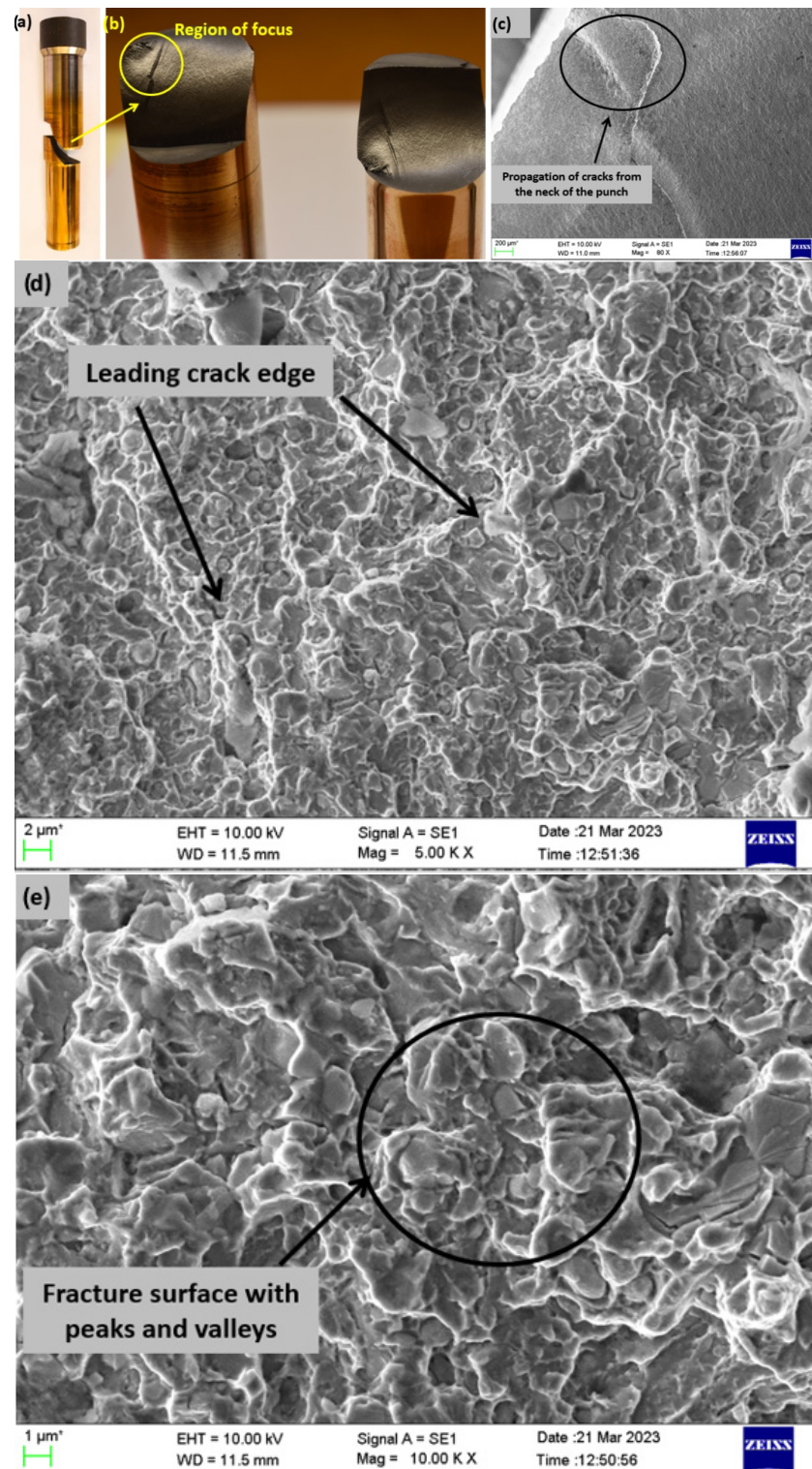


Figure 12. Fracture surface morphology of the S6-1 punch: (a) broken punch, (b) region of focus, (c) crack region on the fractured surface, (d,e) magnified SEM images at 1 and 2 μm. (Note: The * symbol near the scale bar is part of the original SEM image and does not indicate anything specific).

The S2-1 punch failed after 35,103 forged components, with a crack initiating at the neck region that propagated further to punch fracture. In contrast, the S5-3 punch failed after 32,540 forged components due to its high hardness of 64–65 HRC. The SEM images of the fracture zone, as shown in Figure 13, revealed multiple brittle cracks initiating at the punch neck region, which had an abrupt change of section and stress concentration. The

fracture leading edge highlighted in higher-resolution SEM images in Figure 13d,e for PM-grade steels indicated the presence of stretched zones due to fatigue failure. Macroscopic observations of the SEM image in Figure 13c showed stretched zones with a series of cracks that led to catastrophic punch failure. The crack leading edge consisted of a transgranular structure, clearly distinguishing it from other fracture regions.

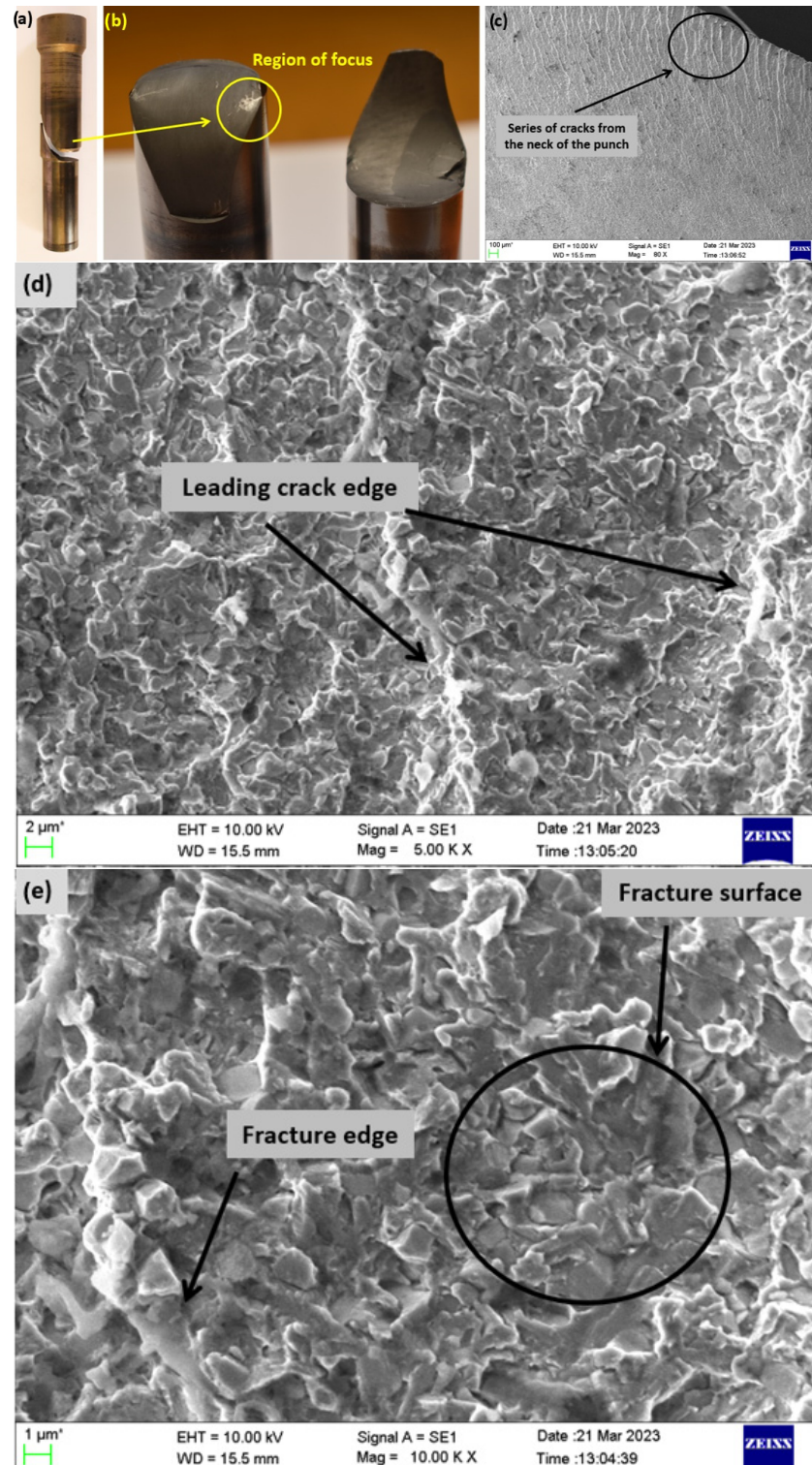


Figure 13. Fracture surface morphology of the S2-1 punch: (a) broken punch, (b) region of focus, (c) crack region on the fractured surface, (d,e) magnified SEM images at 1 and 2 μm . (Note: The * symbol near the scale bar is part of the original SEM image and does not indicate anything specific).

The fracture surfaces of both S6-1 and S2-1 punches had cracks originating at the neck that propagated radially into the punch normal to the applied punch load. Stretched zones and transgranular crack ridges were visible; however, cleavage fracture surfaces were also observed. The high-strength steel punch had a space adjacent to the crack that was relatively smooth, without any evidence of fatigue striations, which are normally characterized in low-strength, improperly heat-treated material, as reported in the literature [14,15]. The cracks originated at brittle phases in the material, like massive carbides and the martensite matrix, which resulted in conglomerated cleavage fracture zones. These cracks further propagated through cleavage and intergranular regions advancing into aggregated precipitates along grain boundaries, forming intergranular fractures that appeared as small dimples. These microscopic metallurgical findings on fatigue fractures substantiated earlier reported investigations [14,15].

The punches coded S6-2, S6-3, S2-2, S2-3, S5-1, and S5-2 reached the set target of 40,000 forgings per punch (stage I and II) with their dimensional integrity maintained for extended service life. It was evident that BÖHLER-grade PM punches, set to optimal geometrical attributes with 60–64 HRC hardness and PVD surface coatings, extended punch life by around 40% as compared to existing HSS in cold forging backward extrusion.

3.3. Analysis of Punch Wear Performance

The wear inspected on punches after every 2000 forge operations in production indicated significant signs of wear after 6000 single-stage operations of backward extrusion of component 1, as shown in Figure 14. The two geometrically optimized HSS punches of component 1 showed wear; however, it had a marginal impact on the dimensional accuracy of the final component since the extruded region was later finish-machined to the required accuracy.

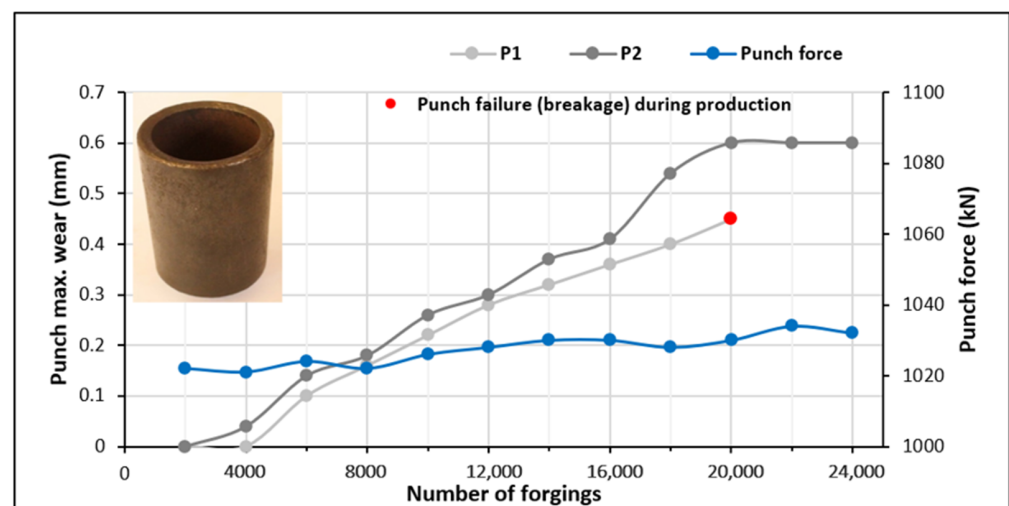


Figure 14. Wear performance of the BE punches: component 1.

The punch wear for two production instances was more or less similar; however, the wear rate exhibited an increasing linear trend with the number of forgings produced. Moreover, the punch for backward extrusion of component 1 during the second instance was stable without further wear during the production of 20,000 to 25,000 components. The punch force marginally increased by less than 1%, contrary to the steep rise in wear by friction due to deteriorated surface conditions. One punch among the two employed for backward extrusion of component 1 fractured at 21,348 load cycles, as shown in Figure 14.

The marginally increased punch force due to its wear was seldom taken into account during production. However, this wear-induced anomaly in the extruded part demanded

secondary machining at the fillet region for intended accuracy and surface finish, as shown in Figure 15. The billet metal flow was affected due to deteriorated contact surface characteristics at the fillet region that led to a meager increase in punch force.

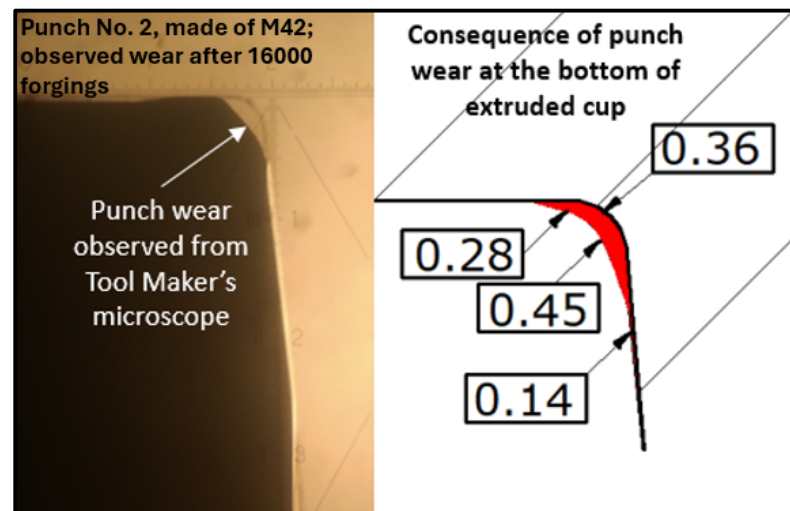


Figure 15. Consequence of the punch wear on the quality of the part: component 1.

The wear profile in Figure 16, generated for component 2 forged with PM-grade punches of varying hardnesses and coatings, was superior compared to the non-coated punches utilized for component 1. The maximum punch wear location with different coating types was identically situated at the fillet region, and coating delamination started early for TiN-coated punches. The TiAlCN-coated punches performed better in terms of wear performance compared to TiN- and AlTiN-coated punches.

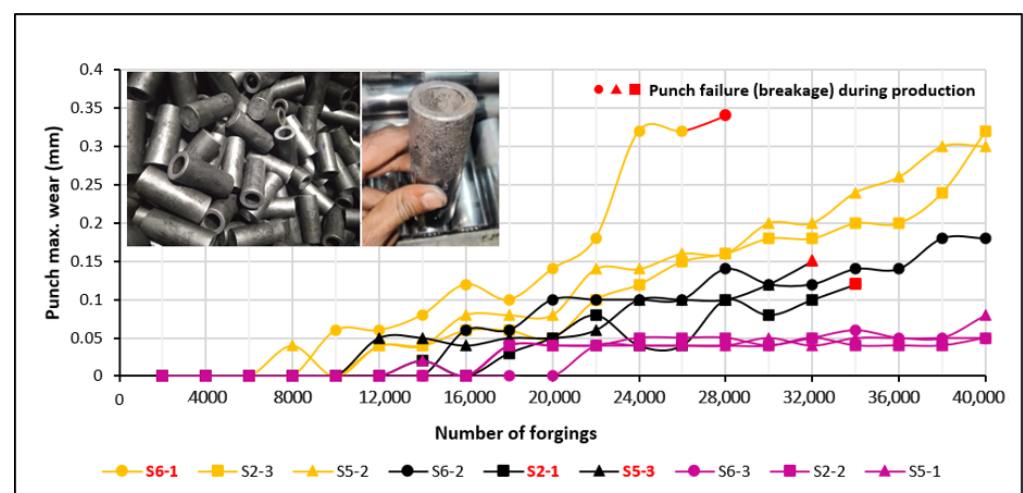


Figure 16. Wear performance of the coated punches: component 2.

As observed in Figure 17, coating delamination (punch wear) occurred in the forging range of 6000–10,000 for TiN-coated punches, whereas wear initiated in the 10,000–14,000 and 12,000–20,000 forging ranges, respectively, for AlTiN- and TiAlCN-coated punches. The punch coatings ranged from 3–5 μm in thickness, among the different punches; the wear performance was excellent for the TiAlCN- compared to TiN- and AlTiN-coated punches.

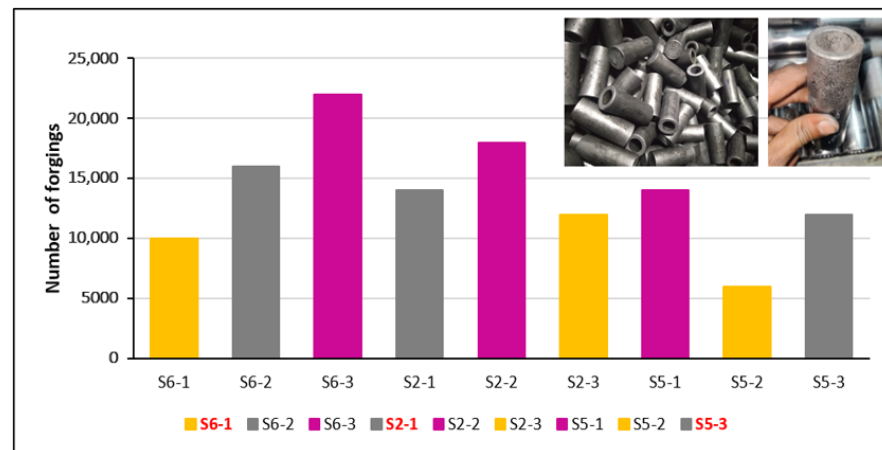


Figure 17. Commencement of coating delamination for coated punches: component 2.

3.4. Analysis of Temperature Effects on Punch Performance

The rise in process temperature influenced the punch (hardness and coating), the billet material (microstructure and strain hardening), and the lubricant (contamination, degradation) [28,41–43]. The periodic punch temperature shown in Figure 18a–c, captured at intervals of 500 forge operations during production, indicated a steady rise.

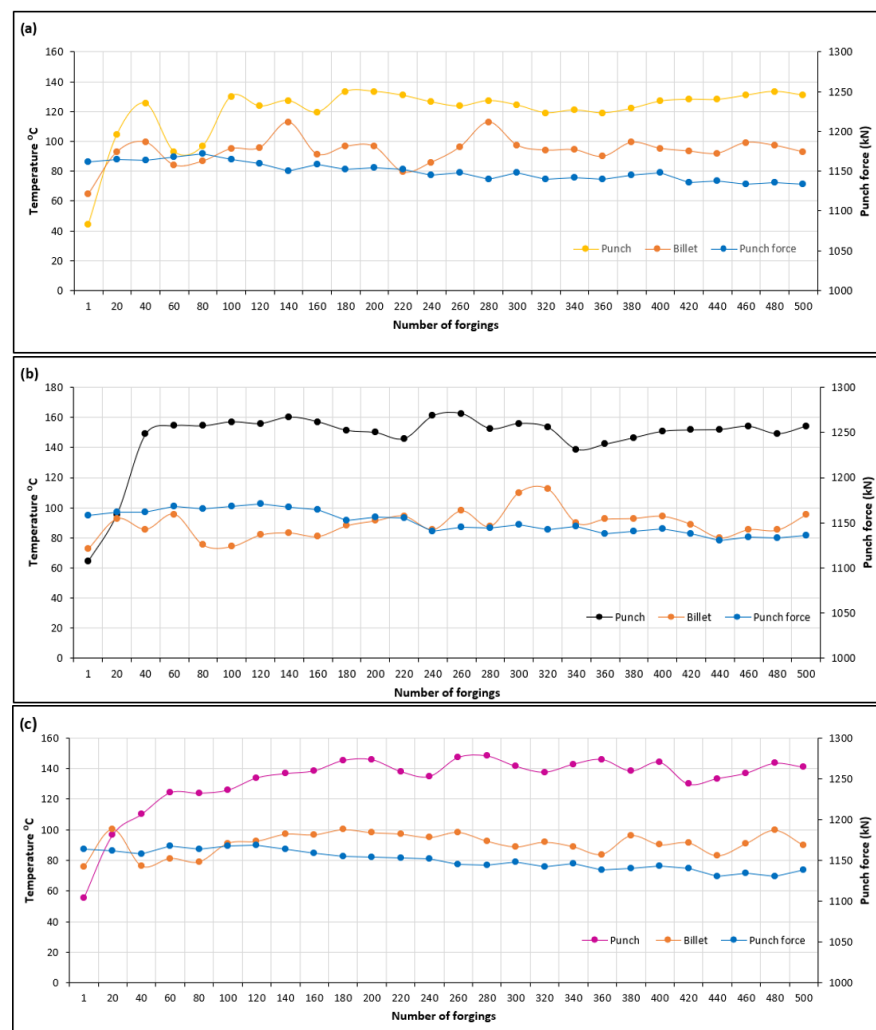


Figure 18. Rise in temperature of the punches for the lot of 500 forgings: component 2. (a) TiN-coated, (b) AlTiN-coated, and (c) TiAlCN-coated punches.

The temperature significantly affected the performance of identically coated punches for the production of 500 forgings, irrespective of their hardness. The time period for each lot was fixed at 5 h during production, with short/long gaps of about 15 or 60 min provided for human needs. The process temperature recorded during two consecutive production runs indicated a significant rise in punch temperature for the initial 40 forge operations, due to high heat dissipation from the billet to the punch.

The billet deformed in every stroke was replaced with a new one; hence, the rise in billet temperature was less significant compared to the punch temperature due to accumulated heat during its continuous operation (transferred from the billet to the punch). The rise in punch temperature in Figure 18a–c indicated a marginal drop in punch force with temperature rise, irrespective of the punch coating, as it readily facilitated plastic deformation of the billet.

The rise in temperature affected punch performance during production, leading to wear and fatigue failures. Figure 19 summarizes the maximum and average temperatures of TiN-, AlTiN-, and TiAlCN-coated punches, indicating that TiN-coated punches had the lowest temperature rise, whereas AlTiN-coated punches exhibited the highest temperature rise.

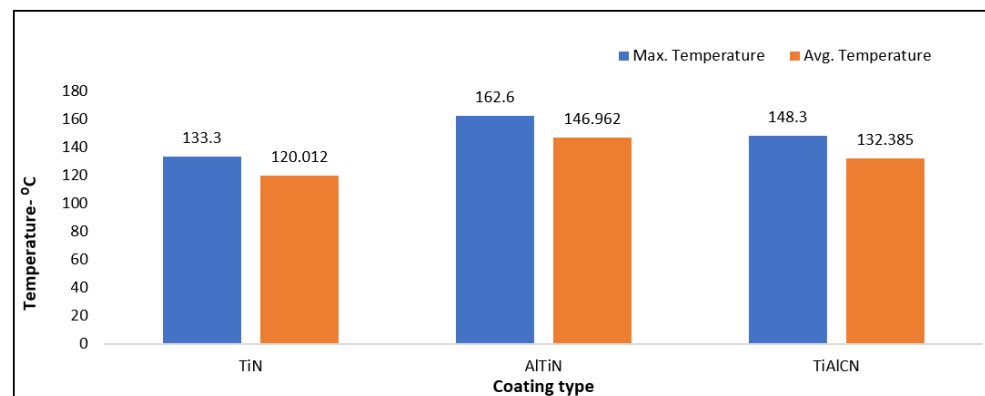


Figure 19. Max. and avg. rise in punch temperatures with different coatings for up to 500 strokes.

The effects of punch manufacturing variables of material, hardness, and coating type on punch performance in Figures 20–22 indicate that the number of forgings produced, maximum wear, and temperature rise are optimal selection criteria for choosing a punch among the L9 possibilities.

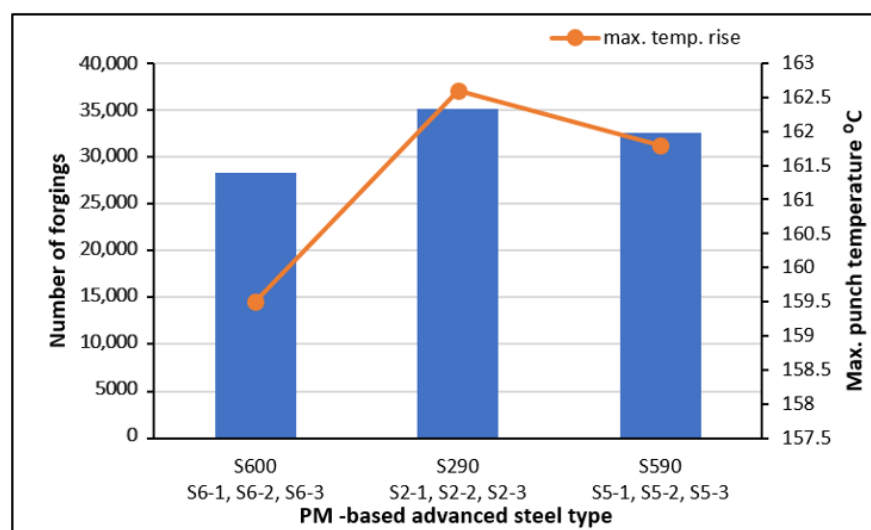


Figure 20. Effect of punch material on performance.

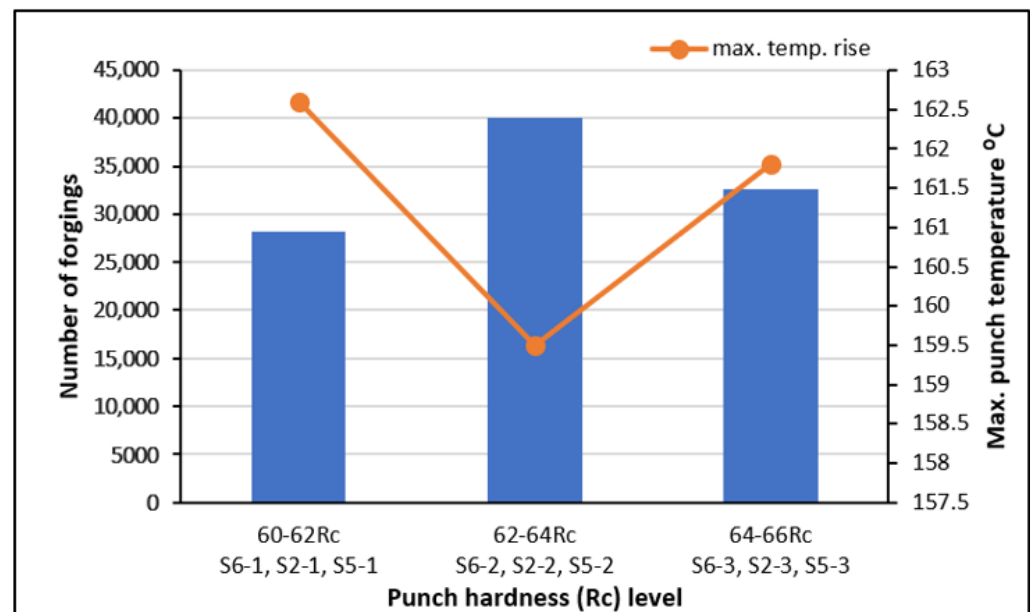


Figure 21. Effect of punch hardness level on performance.

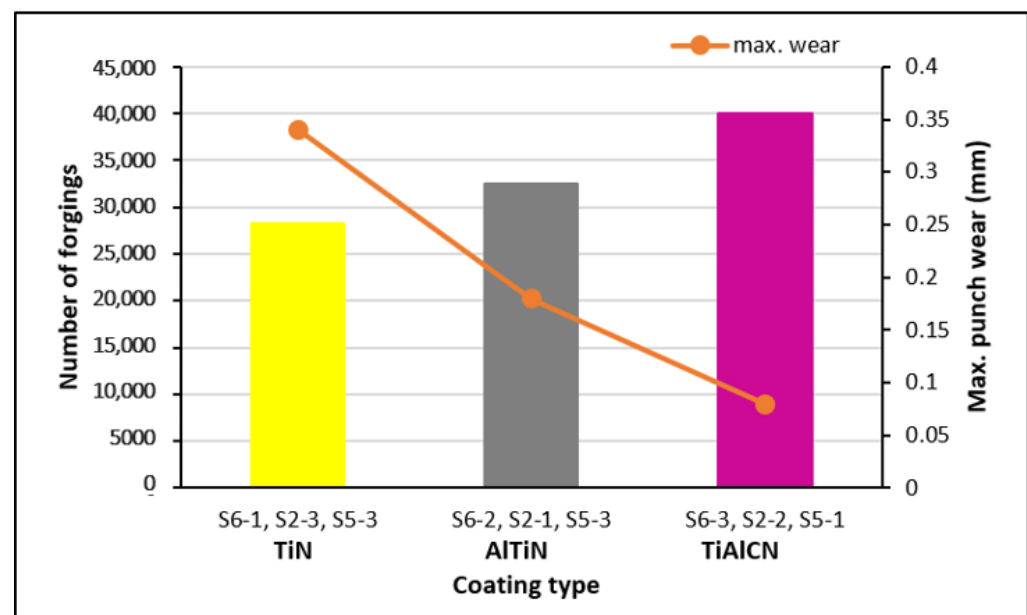


Figure 22. Effect of punch coating type on performance.

The advanced Bohler PM-grade steel punches were investigated to assess the effect of material on punch performance. Figure 20 indicates that S290 PM steel has an upper hand with regard to the number of forgings produced. This differentiation was due to the highest percentage of carbon, vanadium, tungsten, and cobalt (2.0%, 5.12%, 14.12%, and 10.93%, by weight) in S290 steel, which influenced the heat treatment of punches and increased the fatigue strength of the steel (Table 1).

The thermal expansion of the punch material affected accuracy of the extruded components. For BÖHLER-grade PM punch materials, the coefficient of thermal expansion for 100–200 °C was about 10.75×10^{-6} to 11.17×10^{-6} m/(m·K) for S600, 9.6×10^{-6} to 10×10^{-6} m/(m·K) for S290, and 10×10^{-6} to 10.5×10^{-6} m/(m·K) for S590. Though the coefficient of thermal expansion was marginal, the coupled effect of temperature and stresses deteriorated punch performance. The coefficient of thermal expansion of S290 was lower compared to S600 and S590; hence, S290 punches had better performance.

Punch hardness was crucial in minimizing wear and improving performance; however higher hardness led to brittle fractures and lowered fatigue strength that caused catastrophic failure during production. The effect of hardness on punch performance, in Figure 21, illustrated that punches hardened and tempered to 62–64 HRC met target production quantities, while punches with hardness in the range 60–62 HRC and 64–66 HRC fractured at lower load cycles. The forging punch temperature was lower with the 62–64 HRC punch; hence, it was considered better for large volume production, as also validated through SEM images.

The advanced PVD punch coatings, shown in Figure 22, indicate significant improvement in wear and production performance for TiAlCN compared to TiN and AlTiN punches. The main degradation on TiN-, AlTiN-, and TiAlCN-coated punches was due to finish machining scratches, which, although unavoidable, were detrimental to coating behavior. Stress concentration due to these irregularities resulted in delamination or coating chipping that penalized punch life [44]. The PVD coating adhesion characteristics were influenced by the steel base matrix and heat treatment conditions.

The punch performance investigations in cold forging backward extrusion demonstrated that optimal geometric parameters based on component configuration and steel forming behavior were crucial. Additionally, manufacturing variables of material, hardness, and coatings played an important role in determining punch service life.

In the context of industrial production, after evaluating punch performance of PM-based Bohler steel grades, various hardness levels, and surface coatings, it was evident that the S290 punch at 62–64 HRC and coated with TiAlCN was preferred for large-scale production runs. This is supported by Figures 20–22, which illustrate differences in the number of forgings produced, maximum wear, and punch temperature rise during forging load cycles.

The initial target of 40,000 forging operations per punch set, based on the production schedule, was effectively addressed during actual production with the possibility of extended punch life beyond this limit.

3.5. Conclusions

In the current investigation of cold forging backward extrusion in a real-time industry scenario, the study assessed overall punch performance, accounting for advances in manufacturing variables of die material, hardening, and coating. The manufactured punch for the industrial component had optimally designed geometric attributes of steel forming behavior evolved through a preliminary study. The punch performance was compared on the basis of the number of components forged before punch failure due to wear and/or fatigue, as summarized and reported below.

- The HSS punches manufactured for component 1 with optimal geometric attributes showed a marked improvement, with double the production of forgings compared to punches that were used before these industry interventions. The component 2 punch design manufactured with BÖHLER-grade PM material, with improved punch hardness and coatings, bettered performance by around 40% over its predecessor used for component 1. The profiled (counter) punch for forging component 2, stage II, improved threefold when incorporated with optimal geometric attributes.
- The fatigue life of the punch considerably increased with optimal geometric attributes compared to punches of conventional HSS that failed due to fatigue during production. The scanning electron microscopic images showed cracks that further grew into punch fractures. Three out of nine punches with the DoE strategy for type, hardness, and coatings, coded S6-1, S2-1, S5-3, respectively, produced only 28,254, 35,103, and 32,540 forged components before failure. The fractured punch surfaces were analyzed

with SEM, which showed crack propagation initiating from the neck due to stress concentration that led to fatigue punch failure.

- The punch wear data gathered after every 2000 forgings up to 40,000 indicated higher wear for the HSS punch compared to punches with advanced coatings. The punches coated with TiAlCN performed better than those coated with TiN or AlTiN. The wear analysis indicated earlier commencement (6000–10,000 forgings) for TiN-coated punches, whereas it ranged from 12,000 to 20,000 forgings for TiAlCN-coated punches.
- The rise in temperature affected punch performance during production runs and was a major cause of wear and fatigue failures. The maximum and average temperatures of TiN-coated punches had the lowest temperature rise, whereas AlTiN-coated punches exhibited the highest temperature rise.
- The performance evaluation of PM-based Bohler punches with various hardness levels and surface coatings in a production context indicated that the S290 punch, at 62–64 HRC and coated with TiAlCN, was preferred for large-scale production runs.

The current research investigated various factors, including geometric attributes, material composition, heat treatment conditions, coating types, and steel forming that impacted punch performance. The primary objective was to enhance overall punch service life while also accounting for its thermal aspects.

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