

Article

Advanced Manufacturing Technology Based on a Holistic Approach for Improving the Surface Integrity, Wear and Fatigue Strength of Heat-Treated 42CrMo4 Steel Cylindrical Parts

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Abstract

In this study, a sustainable advanced manufacturing technology was developed using a holistic approach for finishing heat-treated 42CrMo4 steel cylindrical parts. The proposed technology is based on a hybrid combined process (HCP) involving cool-assisted dry hard turning and subsequent cool-assisted dry diamond burnishing (DB). A cold-air cooling (without lubrication) condition was achieved using a special device with a cold-air nozzle based on the principle of vortex tubes. The study was conducted in two stages. In the first stage, only the hard turning process was investigated using variance analysis to determine the significant governing factors (feed rate and cutting insert radius). The second stage involved studying and optimising the HCP. This approach incorporated the two significant turning process factors, along with three additional DB process factors: the radius of the diamond insert, burnishing force and feed rate. The selected objective functions were the average roughness, skewness, kurtosis, surface microhardness, residual surface axial stress and fatigue limit. The fatigue limit was determined using the accelerated Locati method. Mathematical models of the objective functions were obtained using experiments and regression analyses. Using multi-objective optimisation, the HCP was optimised based on two criteria: (1) maximum wear resistance under boundary lubrication conditions and (2) maximum fatigue limit. The optimisation tasks were solved by searching for the Pareto optimal solution approach using QStatLab and the NSGA II algorithm. The compromise optimal values of the governing factors, maximising the fatigue limit (690 MPa), are as follows: feed rate in turning and DB of 0.05 mm/rev, radius of the cutting insert of 0.8 mm, diamond insert radius of 2 mm, and burnishing force of 50 N. Experimental verification showed a good agreement with the optimised solutions for surface integrity and fatigue limit characteristics.

Keywords: 42CrMo4; holistic approach; sustainable process; combined hybrid process; surface integrity; wear; fatigue strength

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1. Introduction

The 42CrMo4 grade is a low-alloy structural steel manufactured in accordance with the EN ISO 683-2 standard [1]. This material is usually subjected to quenching and high-temperature tempering to combine high strength and hardness with ductility and impact toughness even at low operating temperatures. 42CrMo4 is more expensive than 41Cr4 steel; however, it is preferred in terms of its material properties. The addition of chromium increases the steel's strength, hardness and corrosion resistance, while molybdenum increases its heat resistance and counteracts the reduction in hardness during tempering by transforming the residual austenite through secondary hardening [2]. 42CrMo4 steel is widely used in the mechanical and automotive engineering sectors to produce high-strength components, including compressors, turbines, working elements of heavy ground and underground equipment, agricultural machinery parts, gears, crankshafts, connecting rods, drill pipes for oil exploration, axles, shafts, etc.

Shafts and axles are integral to converting rotational motion, making them some of the most common machine elements [3]. They are loaded in rotational bending (axles) or in simultaneous bending and torsion (shafts), making fatigue a significant problem in these machine elements. The surface layers of these components are subjected to the most load due to their contact with other parts. They also experience the greatest working stresses and are often exposed to aggressive environments. Therefore, shafts and axles require high hardness, strength, and wear resistance in their surface layers and high impact toughness in their core. Hardened, high-temperature-tempered 42CrMo4 steel is a suitable candidate to meet these material requirements.

The hardness of the surface layer of this steel can be further increased by surface hardening using flame, induction, laser beam, or electron beam methods [4] or nitriding [5,6]. Alternatively, a significantly cheaper approach is surface cold working (SCW), which is based on severe surface plastic deformation and improves the material's surface integrity (SI), increasing its surface microhardness and introducing residual compressive stresses to a depth of up to 0.8 mm [7]. SCW can be achieved through dynamic (impact-based) or static methods. The latter (known as burnishing methods) markedly improves the surface texture, combined with a surface-hardening effect and the introduction of useful residual compressive stresses, making them particularly suitable for finishing axles and shafts with circular cross-sections. Depending on the tangential contact between the deforming element and the machined surface, burnishing methods can be realised with rolling contact (roller or ball burnishing) or sliding friction contact (slide burnishing). When the deforming element in slide burnishing is a natural or artificial cylindrical-ended or spherical-ended diamond, the method is called diamond burnishing (DB). Six decades ago, General Electric developed DB to improve the SI of metal components [8].

Numerous studies have investigated improving the SI and operating behaviour of 42CrMo4 steel through burnishing processes. Using hydrostatic ball burnishing, Swirad and Pawlus [9] improved the tribological behaviour of flat 34 HRC specimens. Additionally, Dzierwa and Markopoulos [10] studied the effect of slide burnishing on the surface topography of flat 46 HRC specimens using a tungsten carbide deforming ball with a diameter of 6 mm. These authors identified a correlation between several 3D roughness parameters and the level of volumetric wear. DB was also performed using a cylindrical-ended polycrystalline diamond insert to improve SI in several studies [11,12]. Using Hartley's experimental scheme, Swirad [11] investigated the influence of DB governing factors on the 3D roughness parameters of 15 cylindrical specimens of 32 HRC, with the Sa height parameter reduced from 0.63 to 0.0497 μm through applying DB. Using the same experimental design, Korzynski et al. [12] also established the effects of DB governing factors on Sa height roughness parameters and the fatigue limit of 32 HRC specimens, with an observed reduction in Sa from 0.63 to 0.054 μm and a fatigue limit improvement of 18%

compared to the ground specimen. Kluz et al. [13,14] investigated the effect of DB on the 2D surface roughness parameter Ra of 22 HRC cylindrical specimens using Hartley's experimental design and a spherical-ended polycrystalline diamond insert. Using the same type of diamond deforming element, Zaghal et al. [15] significantly improved the SI of 54 HRC specimens. Kebede et al. [16] developed a new feed-varying multi-pass DB process to improve the height and shape 3D roughness parameters of cylindrical specimens, using 42CrMo4 in its as-received state.

Combined processes involving sequential impacts have also been developed to improve the performance of 42CrMo4 steel components. Terres et al. [17] investigated the effects of nitriding and nitriding + shot peening on high-cycle, three-point bending fatigue behaviour of quenched and high-tempered notched specimens. Their study found that the combined approach increased the specimen's fatigue limit by 35%, while the increase observed from nitriding alone was 8%. Additionally, Maximov et al. [18] developed an optimised sustainable combined process, including sequential dry hard turning and dry DB to improve the SI and fatigue strength of 33 HRC shafts and axles.

DB, as a finishing process, is performed on the same machine tool as turning. Conventional processes involve using cutting fluid (CF) to reduce heat generation, flush chips from the cutting zone in the turning process and inhibit corrosion to improve the material's surface quality, reduce tool wear and increase efficiency [19]. However, CF usage can cause significant economic, environmental and health problems. The cost of CF can reach up to 20% of the total cost of the product [20]; disposing of even purified CF can cause pollution of rivers, lakes, air and groundwater [19], and CF is harmful to human health, with potential impacts including skin infections, pneumonia and lung cancer [21–23]. To mitigate these problems, alternative approaches such as minimal lubrication [24], cryogenic machining [25] and dry cutting [26] have been proposed to minimise CF usage in the turning process. Specifically for DB, these approaches are applied as cryogenic-assisted [27], cool-assisted [28] and dry [29] DB. These processes are sustainable because they are environmentally friendly, more economically efficient and pose reduced health risks relative to CF [30].

Of the three sustainable process options, dry DB is the cheapest, while cryogenic-assisted DB (below $-180\text{ }^{\circ}\text{C}$) requires the use of specialist equipment. The cool-assisted process is intermediate in terms of its economic efficiency, and using a device with a cold air nozzle based on the vortex tube principle is easy to implement. As an example, Van et al. [28,31] developed optimised cool-assisted DB of internal cylindrical surfaces on 42CrMo4 steel specimens (in as-received state) utilising a cold air–cryogenic CO₂-assisted process. Additionally, Korzynski et al. [12] employed dry DB for finishing 32 HRC 42CrMo4 steel specimens.

A sustainable combined process was developed in our previous study, involving sequential dry hard turning and dry DB to improve the SI and fatigue strength of 33 HRC 42CrMo4 steel shafts and axles [18]. A holistic approach was employed using a sequential method where the two studied processes were considered independently. The initial hard turning step was optimised first, and then DB was implemented as a smoothing process with three burnishing force magnitudes (50, 100 and 150 N). However, these two processes are interrelated, as the effect of DB is not independent of the initial SI obtained from turning. Independent optimisation of the two processes does not fully reflect their correlation; therefore, to ensure a synergistic effect, optimisation of the combined process is necessary. To address this, the present study's main objective is to develop an integrally optimised, sustainable hybrid combined process (HCP), including successive cool-assisted dry hard turning and cool-assisted dry DB of heat-treated 42CrMo4 steel cylindrical parts.

2. Materials and Methods

2.1. Material

The studied 42CrMo4 steel was received as 26 mm hot-rolled cylindrical bars. These bars were then cut into 250 mm long blanks. The blanks were then heat-treated using the following steps. (1) Normalisation: Heating to 850 °C, holding for one hour and then air cooling to room temperature. (2) Quenching: Heating to 860 °C, holding for 30 min and quenching in oil. (3) Tempering: Heating to 590 °C, holding for three hours and subsequent air cooling.

The chemical composition of the steel in terms of mass percentage was measured using an optical emission spectrometer (Foundry-Master Optimum, Hitachi, Tokyo, Japan) with a resolution of 0.001. The main mechanical characteristics of the specimens were determined from the arithmetic means of the results of three tests conducted at room temperature. A Zwick/Roell Vibrophore 100 testing machine (Ulm, Germany) and a KM-30 Charpy universal impact tester (SU) with 300 J impact energy were used for tensile and impact toughness tests, respectively. The tensile and impact toughness specimen geometries were performed according to ISO 6892-1:2019 and ISO 26843:2015 standards [32,33], respectively. A VEB-WPM tester (Markkleeberg, Germany) with a spherical-ended indenter with a diameter of 2.5 mm, a load of 62.5 kg, and a holding time of 10 s was used to calculate the hardness based on the arithmetic mean of five measurements.

2.2. HCP Implementation

The HCP was implemented on an Index Traub CNC lathe under cold air cooling conditions (without lubrication) using a specialist device (Emuge-Franken, Lauf an der Pegnitz, Germany) with a cold air nozzle, whose function is based on the principle of vortex tubes (Figure 1). VCMT 160404-F3P carbide cutting inserts, which were used in the experiments after the running-in stage and before flank wear, and an SVVCN 2525M-16 holder for the turning process were provided by ISCAR Bulgaria (Sofia, Bulgaria). The applied DB device provided elastic normal contact between the deforming diamond insert and the treated surface. Single-pass DB was implemented using a spherical-ended polycrystalline diamond insert with a sliding velocity of 80 m/min.

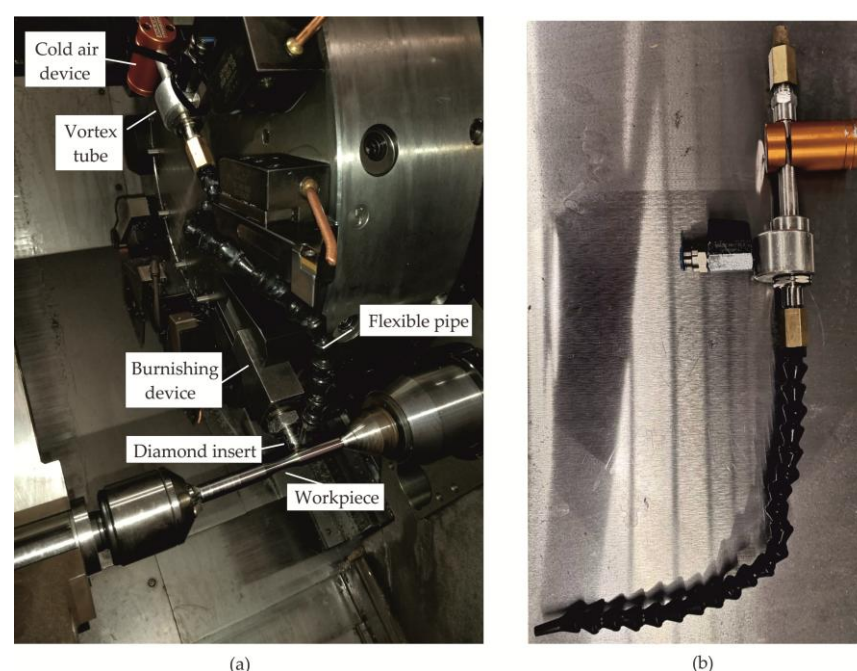


Figure 1. Implementation of the HCP: (a) DB operation and (b) general view of the cold air device.

2.3. Measurement of SI Characteristics

In this work, the 2D roughness parameters were measured using a Mitutoyo Surftest SJ-210 surface roughness tester (Kawasaki, Japan). The cut-off length and the evaluation length were 0.25 and 0.4 mm, respectively, and the average arithmetic values were calculated based on six equally spaced sample generatrices. A ZHV μ Zwick/Roell microhardness tester (Ulm, Germany) was used to measure the surface microhardness with a 0.05 kgf load and 10 s holding time. The final surface microhardness value was taken as the median of 10 measurements. A Bruker D8 Advance X-ray diffractometer (Billerica, MA, USA) with a pinhole collimator with a primary beam measuring 1×1 mm was used to measure the axial residual stresses. The characteristics of the residual stress X-ray measurement were presented in detail in our previous study [18]. The specimens' microstructure was observed using scanning electron microscopy (SEM; Zeiss Evo 10, Jena, Germany).

2.4. Fatigue Tests

Rotating bending fatigue tests were conducted on a UBM testing machine (Markkleeberg, Germany) at room temperature in air. The loading frequency was 50 Hz. Each hourglass-shaped specimen with a minimum diameter of 7.5 mm was tested to complete destruction. The specimen geometry was chosen based on Bulgarian National Standard 5297:1983 [34]. Locati's accelerated method was used to determine the fatigue limits. This method is based on the Palmgren–Miner linear damage hypothesis, which is a particular case of a general cumulative damage theory [35]. To determine the fatigue limit, the method requires only one specimen that is subjected to a stepwise increasing load (Figure 2a). The difference ($\Delta\sigma$) in the stress amplitudes between any two adjacent levels and the number of cycles (n) for each step are constants. The load is increased until the test specimen fails. To calculate the fatigue limit, a minimum of three assumed S-N curves is required. The difference $\Delta\sigma_{-1}$ between the fatigue limits of two adjacent S-N curves is a constant value, and the curves are equidistant. According to the linear hypothesis, failure occurs when the sum of accumulated damages D is equal to unity:

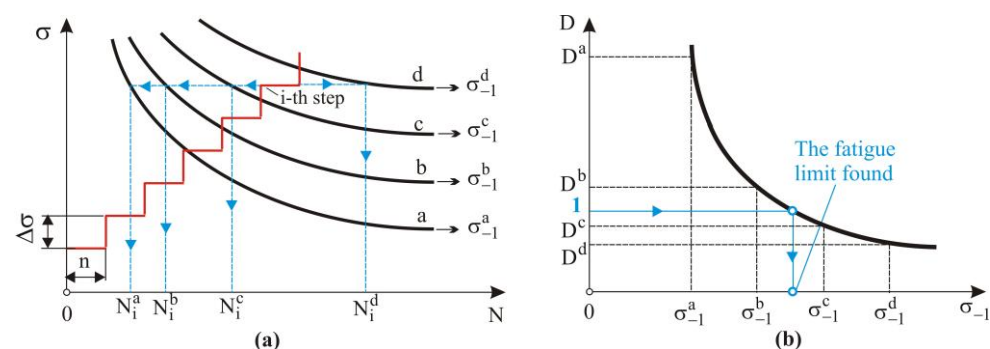


Figure 2. Illustration of Locati's method: (a) stepwise increasing load (in red) and determination of the number of cycles to failure for each step (in blue); (b) fatigue limit–damage curve (in black) and determination of the fatigue limit (in blue).

$$D = \sum_{i=1}^k (n_i / N_i) = 1,$$

where k is the number of steps, and N_i is the number of cycles to failure at the i -th load step for the corresponding S-N curve.

For each of the selected fatigue curves, the sum of accumulated damage D is calculated. The obtained values are plotted in the fatigue limit–sum of accumulated damage D

coordinate system. The stress obtained by interpolating for $D = 1$ on the fatigue limit–damage curve represents the specimen’s fatigue limit (Figure 2b).

In this study, five specimens were used for each data point, and the fatigue limit was calculated as the arithmetic mean of the five studied specimens.

3. Results and Discussion

3.1. Material Characterisation

The chemical composition of the as-received 42CrMo4 in wt % was identified in our previous study [18] as follows: Fe—97.1, C—0.463, Si—0.193, Mn—0.842, P—0.0082, S—0.0063, Cr—1.07, Mo—0.183 and Ni—0.0066 (Al, Nb, Cu, V, Pb, Co, Ti and W—balance). The mechanical characteristics (nominal values and deviations) are given in Table 1. Compared to the as-received state, heat treatment dramatically increased the static strength, impact toughness and hardness of the steel and moderately increased its plastic elongation.

Table 1. Mechanical characteristics (nominal values and deviations) of the used 42CrMo4 steel.

Material State	Yield Limit, MPa	Tensile Strength, MPa	Elongation, %	Hardness, HB	Impact Toughness, J/cm ²
As-received	708 ⁺² _{−1}	747 ^{±1}	10.9 ^{+0.1} _{−0.2}	233.7 ^{+0.9} _{−1.2}	64 ^{±2}
Heat-treated	967 ⁺¹⁴ _{−8}	1046 ^{±8}	12.9 ^{±0.1}	307.4 ^{+5.2} _{−4.7}	112 ⁺³ _{−2}

The structure of the 42CrMo4 steel in its as-received state is ferrite–perlite (Figure 3a), with the lighter areas in the image representing cementite and the darker areas ferrite. The structure obtained after heat treatment is shown in Figure 3b. The martensitic structure obtained after quenching undergoes changes during the tempering process. The presence of chromium and molybdenum greatly complicates the breakdown of martensite, reducing the rate of diffusion and raising the onset temperature for martensite breakdown. This process is further complicated by the formation of complex carbides of the type FeCrMo₃C, which have an elongated lamellar shape. The breakdown of martensite leads to a significant reduction in deformation and microstress within the crystal structure. The resulting structure has a lower free energy and a more stable state, providing a favourable combination of mechanical characteristics (see Table 1).

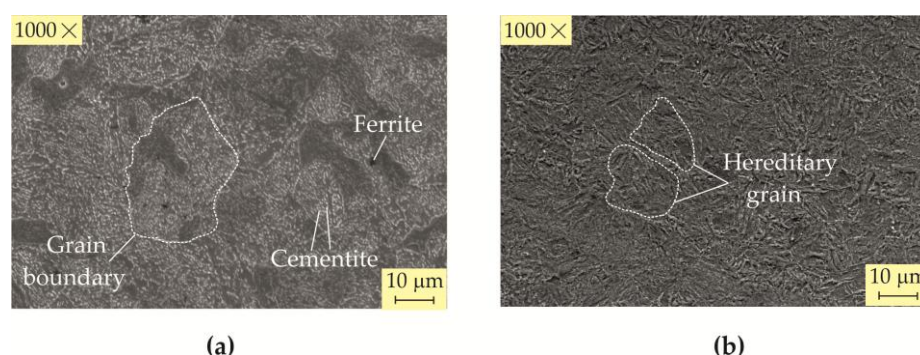


Figure 3. Evolution of the microstructure of the used 42CrMo4 steel in (a) as-received and (b) heat-treated specimens.

3.2. Cool-Assisted Dry Turning

This section aims to assess the significance (i.e., the degree of influence on a selected SI characteristic) of all the governing factors of cool-assisted dry turning and select the

most significant factors. This selection, along with the identified governing factors of the cool-assisted dry DB process, will form the set of governing factors for the HCP, which will be further investigated and optimised.

3.2.1. Specimens

The heat-treated specimens on which the roughness parameters were measured after cool-assisted dry turning were cylindrical with a nominal diameter of 24 mm and a length of 40 mm.

3.2.2. Governing Factors, Levels and Objective Functions

The governing factors of the turning process were the cutting velocity v_c , feed rate f_c , cutting depth a_c , radius of the cutting insert R , and main setting angle χ_r (Table 2). The relationship between the natural and coded variables ($\tilde{x}_i$ and x_i , respectively) can be expressed as follows:

Table 2. Governing factors and their levels in the turning process.

Governing Factors	Level							
	Natural $\tilde{x}_i$				Coded x_i			
Cutting velocity v_c , m/min	$\tilde{x}_1$	50	115	180	x_1	−1	0	+1
Feed rate f_c , mm/rev	$\tilde{x}_2$	0.05	0.125	0.2	x_2	−1	0	+1
Cutting depth a_p , mm	$\tilde{x}_3$	0.1	0.55	1	x_3	−1	0	+1
Cutting insert radius R , mm	$\tilde{x}_4$	0.4	0.8	1.2	x_4	−1	0	+1
Main setting angle χ_r , °	$\tilde{x}_5$	72.5	n.a.	93	x_5	−1	n.a.	+1

$$x_i = \frac{(\tilde{x}_i - \tilde{x}_{i,0})}{(\tilde{x}_{i,\max} - \tilde{x}_{i,0})},$$

where $\tilde{x}_{i,0}$ and $\tilde{x}_{i,\max}$ are the average and maximum values of the natural variable, respectively.

The objective function is the roughness parameter R_a , the most commonly used height roughness parameter in engineering practice. A planned experiment and composition design, in accordance with governing factors and their levels, was used (Table 3).

Table 3. Experimental design and roughness results obtained via turning.

No	v_c f		a_c	R	χ_r	R_a , μm	R_{sk}	R_{ku}
	x_1	x_2	x_3	x_4	x_5			
1	−1	−1	−1	−1	−1	1.530	0.382	2.740
2	1	−1	−1	1	−1	0.241	0.164	2.242
3	−1	1	−1	1	1	1.102	0.688	2.188
4	1	1	−1	−1	1	3.393	0.675	2.339
5	−1	−1	1	1	1	0.290	−0.896	2.720
6	1	−1	1	−1	1	0.511	0.596	2.515
7	−1	1	1	−1	−1	2.705	0.724	2.340
8	1	1	1	1	−1	0.929	0.580	2.414
9	−1	0	0	0	−1	2.532	−0.287	2.407
10	1	0	0	0	−1	0.527	0.242	1.813
11	0	−1	0	0	1	0.204	−0.041	2.670
12	0	1	0	0	1	1.496	0.558	2.108

13	0	0	−1	0	−1	0.555	0.259	2.173
14	0	0	1	0	−1	0.599	0.036	2.621
15	0	0	0	−1	1	1.525	0.676	2.228
16	0	0	0	1	1	0.436	0.406	2.231

3.2.3. Results

The experimental results for the roughness parameter R_a are shown in Table 3. In addition, the results for the skewness and kurtosis shape roughness parameters, on which the wear resistance of the treated surface under the boundary lubrication condition directly depends, are also shown [36].

An analysis of variance (ANOVA) was performed for the three selected roughness parameters using QStatLab software, v. 6.1.1.3 [37]. The computed ANOVA results are listed in Table 4. The probability of a governing factor being significant is $\alpha = 0.05$, i.e., a confidence level of 95%. The significant factors for the R_a roughness parameter were the feed rate (x_2) and cutting insert radius (x_4), while all five governing factors were found to be insignificant for the skewness and kurtosis parameters. Figure 4 illustrates the influence of the controlling factors on the three roughness parameters.

Table 4. Computed ANOVA results for the turning process.

Objective Function	Source	Sum of Squares	Dispersion	F Value	p Value
Ra roughness parameter	Cutting velocity x_1	1.88772	0.94386	2.36936	0.17442
	Feed rate x_2	4.85799	2.42900	6.09747	0.03586
	Cutting depth x_3	0.33543	0.16771	0.42101	0.67438
	Cutting insert radius x_4	4.73903	2.36951	5.94816	0.03768
	Main setting angle x_5	0.02731	0.02731	0.06855	0.80222
	Residual	2.39017	0.39836		
	Total	14.23764			
	Residual standard deviation = 0.63116; R-sq = 0.83212; R-sq (adj) = 0.58031				
Skewness Rsk	Cutting velocity x_1	0.76241	0.38120	1.01959	0.41574
	Feed rate x_2	1.61769	0.80885	2.16339	0.19614
	Cutting depth x_3	0.45831	0.22916	0.61291	0.57252
	Cutting insert radius x_4	1.07834	0.53917	1.44210	0.30803
	Main setting angle x_5	0.01199	0.01199	0.03207	0.86377
	Residual	2.24328	0.37388		
	Total	6.17202			
	Residual standard deviation = 0.61146; R-sq = 0.63654; R-sq (adj) = 0.09135				
Kurtosis Rku	Cutting velocity x_1	16.26283	8.13141	1.64792	0.26890
	Feed rate x_2	18.46050	9.23025	1.87061	0.23368
	Cutting depth x_3	17.22012	8.61006	1.74492	0.25274
	Cutting insert radius x_4	13.79253	6.89626	1.39760	0.31748
	Main setting angle x_5	6.56513	6.56513	1.33049	0.29259
	Residual	29.60611	4.93435		
	Total	101.90721			
	Residual standard deviation = 2.22134; R-sq = 0.70948; R-sq (adj) = 0.27370				

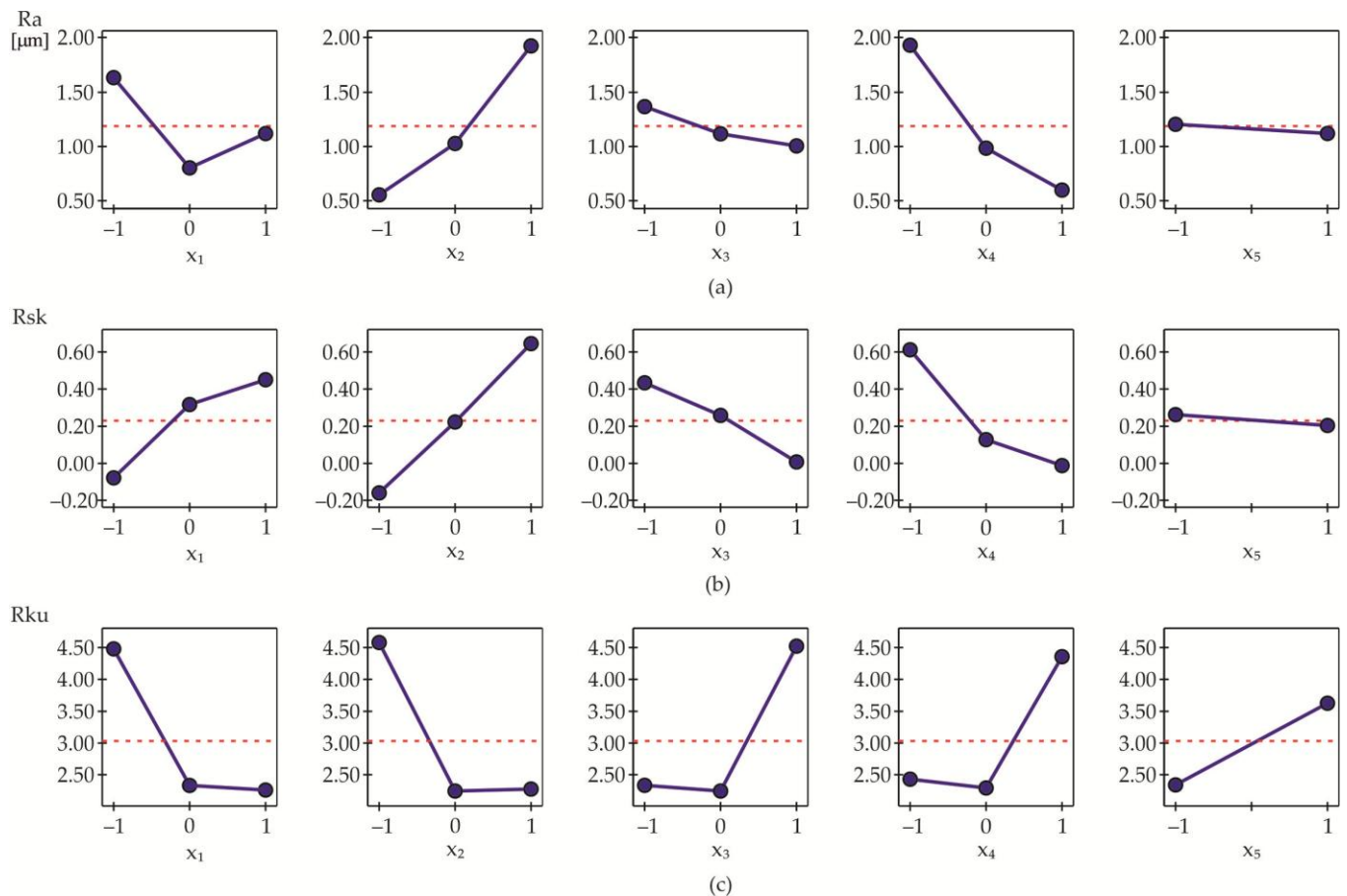


Figure 4. ANOVA of the main effects in the turning process: (a) Ra roughness parameter; (b) skewness Rsk; (c) kurtosis Rku.

3.2.4. Selecting Governing Factors for the Sustainable HCP

Of the five governing factors of the turning process, the two factors identified as significant (feed rate f_c and cutting insert radius R) were selected for the sustainable HCP. The other factors were maintained at constant levels corresponding to the lowest values of the Ra roughness parameter, as follows: $v_c = 115 \text{ m/min}$, $a_p = 0.5 \text{ mm}$ and main setting angle $\chi_r = 93^\circ$.

3.3. Sustainable HCP—Modeling, Investigation and Optimisations

3.3.1. Governing Factors and Their Levels

Turning and DB (both performed under cool-assisted dry conditions) were conducted during one clamping process, thus realising sustainable HCP. The selected governing factors are as follows: (1) the feed rate f_c and cutting insert radius R in the turning process, and (2) the diamond radius r, burnishing force F_b , and feed rate f in the DB process. The levels of the governing factors are shown in Table 5. The parameter values relating to DB are selected based on prior experience of DB of heat-treated 42CrMo4 steel [15,18,38]. The burnishing velocity was set to 80 m/min to limit the influence of the thermal effect. A planned experiment, utilising a second-order optimal composition design, was performed (Table 6). The core of this design (i.e., the first eight experimental points) was a fractional replicate, aiming to reduce the total number of experimental points.

Table 5. Governing factors and levels in the HCP.

Governing Factors		Levels						
		Natural, $\tilde{x}_i$			Coded, x_i			
Feed rate (turning) f_c , mm/rev	$\tilde{x}_1$	0.05	0.125	0.2	x_1	−1	0	1
Cutting insert radius R_c , mm	$\tilde{x}_2$	0.4	0.8	1.2	x_2	−1	0	1
Diamond radius r , mm	$\tilde{x}_3$	2	3	4	x_3	−1	0	1
Burnishing force F_b , N	$\tilde{x}_4$	50	100	150	x_4	−1	0	1
Feed rate (DB) f , mm/rev	$\tilde{x}_5$	0.03	0.05	0.07	x_5	−1	0	1

Table 6. Experimental design and results obtained via HCP.

N_0	f_c x_1	R_c x_2	r x_3	F_b x_4	f x_5	R_a , μm	R_{sk}	R_{ku}	HV0.05	ResStr MPa	σ_{-1} MPa
1	−1	−1	−1	−1	−1	0.064	−0.158	4.237	708	−1172.6	642
2	1	−1	−1	1	−1	0.149	−0.078	2.799	707	−1330.5	637
3	−1	1	−1	1	1	0.135	0.021	5.462	543	−1035.8	644
4	1	1	−1	−1	1	0.135	−0.958	5.875	495	−966.6	625
5	−1	−1	1	1	1	0.128	−1.050	4.388	916	−1078.3	627
6	1	−1	1	−1	1	0.516	−0.274	1.941	669	−691.2	646
7	−1	1	1	−1	−1	0.070	−1.287	5.657	516	−811.8	682
8	1	1	1	1	−1	0.044	−0.151	2.798	460	−882.5	645
9	−1	0	0	0	0	0.076	−0.800	4.241	466	−809.1	646
10	1	0	0	0	0	0.147	−0.298	2.720	461	−774.4	639
11	0	−1	0	0	0	0.097	−0.078	3.013	678	−740.3	587
12	0	1	0	0	0	0.101	−0.171	2.779	508	−732.6	624
13	0	0	−1	0	0	0.127	−0.085	2.791	425	−846.5	650
14	0	0	1	0	0	0.094	−1.895	11.835	430	−823.3	653
15	0	0	0	−1	0	0.111	−0.490	4.880	427	−773.6	653
16	0	0	0	1	0	0.077	−0.017	3.771	425	−814.8	647
17	0	0	0	0	−1	0.126	−0.794	5.086	417	−757.6	629
18	0	0	0	0	1	0.125	−0.724	5.523	442	−801.1	615

3.3.2. Objective Functions and Experimental Results

The selected objective functions were the average roughness Y_{Ra} , skewness Y_{sk} , kurtosis Y_{ku} , surface microhardness Y_{HV} , residual surface axial stress $Y_{\sigma_{res}}$ and fatigue limit $Y_{\sigma_{-1}}$. These objective functions were selected for the following reasons: (1) the R_a roughness parameter is representative of the height (amplitude) of the material's surface and is the most widely used roughness parameter in engineering practice; (2) the shape roughness parameters (skewness and kurtosis) play a significant role in the operating behaviour of the finished surfaces [36,39]; (3) the surface microhardness and residual stress are the main mechanical characteristics of SI; and (4) the fatigue limit is a key characteristic of fatigue behaviour.

Figure 5 shows the selected S-N curves according to Locati's method, obtained from an experimentally determined curve [18] generated using fatigue specimens fabricated solely by turning and polishing under flood lubrication. The stress amplitude increased in steps of 20 MPa, and the number of cycles for each step (excluding the final step, where the test specimen failed) was 10^5 cycles.

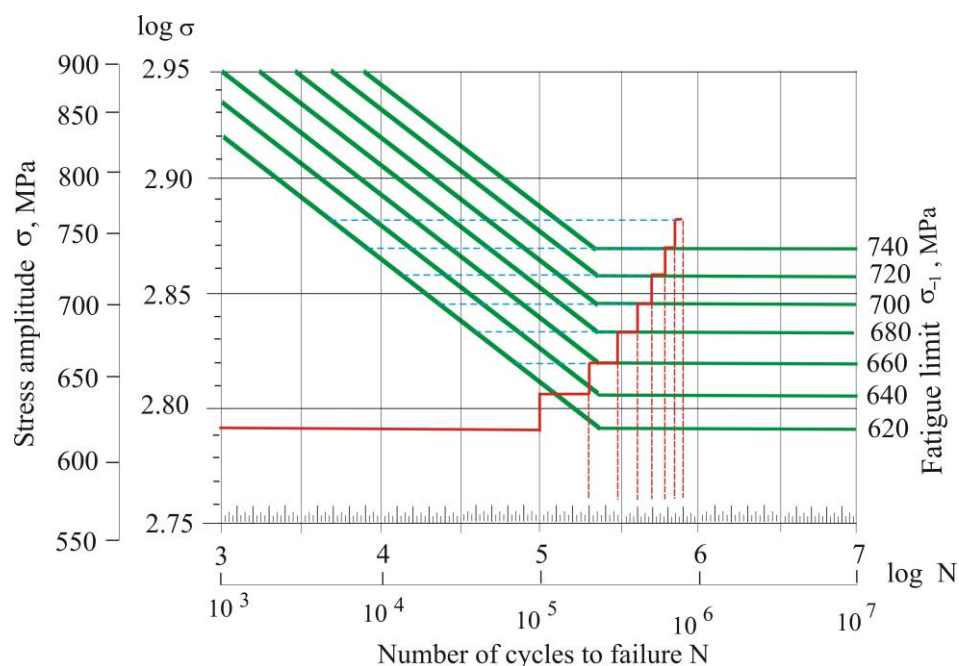


Figure 5. Assumed S-N curves.

The experimental results from the HCP are listed in Table 6.

3.3.3. Regression Analyses

Regression analyses were performed using QStatLab. Given the chosen experimental design, the approximating polynomials are of no higher than second order:

$$Y^{(k)}(\{X\}) = b_0^{(k)} + \sum_{i=1}^3 b_i^{(k)} x_i + \sum_{i=1}^2 \sum_{j=i-1}^3 b_{ij}^{(k)} x_i x_j + \sum_{i=1}^3 b_{ii}^{(k)} x_i^2, \quad k = 1, 2, 3$$

where $\{X\}$ is the vector of the governing factors x_i , and $k = 1, \dots, 6$ represents the corresponding objective function. The polynomial coefficients of the models are listed in Table 7.

Table 7. Polynomial coefficients.

Coefficients	Models					
	Y_{Ra}	Y_{sk}	Y_{ku}	Y_{HV}	$Y_{\sigma_{res}}$	$Y_{\sigma_{-1}}$
b0	0.09634375	−0.54631132	4.79371880	428.12264000	−732.9857100	632
b1	0.03550000	0.25100000	−0.78520000	−2.50000000	0	−3.5
b2	0.00200000	−0.04650000	−0.11700000	−85.00000000	0	18.5
b3	−0.01650000	−0.90500000	4.52200000	2.50000000	0	1.5
b4	−0.01700000	0.23650000	−0.55450000	−1.00000000	0	−3
b5	0	0	0.26120000	12.50000000	37.20000000	−7
b11	0.01515625	0	−1.31321870	35.16981100	−73.4285710	10.5
b22	0.00265625	0.42091509	−1.89771870	164.66981000		−26.5
b33	0.01415625	−0.44458491	2.51928120	0	−116.5785700	19.5
b44	−0.00234375	0.29191509	−0.46821875	−2.33018870	−75.8785710	18
b55	0.02915625	−0.21358491	0.51078125	1.16981130	0	−10
b12	−0.06237500	−0.08737500	0.17987500	18.00000000	0	−8.75
b13	0.03462500	0.35137500	−0.53512500	−31.75000000	0	0
b14	0	0	0	0	0	0
b15	0.02412500	0.05912500	−0.27162500	−30.75000000	66.9875000	2.25

b23	−0.07337500	0.07337500	0	−16.50000000	0	1
b24	0	0	0	0	0	0
b25	−0.05087500	−0.70637500	4.97062500	−11.00000000	−131.5875000	−5
b34	0	0	0	0	0	0
b35	0.06112500	0.05537500	−0.92037500	38.25000000	−70.6125000	13
b45	−0.02037500	0.12437500	0	41.50000000	0	1.75

A statistical analysis of the models was performed using QStatLab software. The ANOVA results for the models are listed in Table 8. The probability values P_i are much smaller than $\alpha = 0.05$, indicating that the observed trends are statistically significant and thus unlikely to be random.

Table 8. Computed ANOVA results for the regression models.

Model	Source	Sum of Squares	Degrees of Freedom	Dispersion	F Value	p Value
Y_{Ra}	Model	0.17440	16	0.01090	21,799.437	0.00532
	Residual	5×10^{-7}	1	5×10^{-7}		
	Total	0.17440	17			
Y_{sk}	Model	4.76933	15	0.31796	257.3199	0.00388
	Residual	0.00347	2	0.00124		
	Total	4.77180	17			
Y_{ku}	Model	83.68566	15	5.57904	1834.1711	0.00055
	Residual	0.00608	2	0.00403		
	Total	83.69175	17			
Y_{HV}	Model	330,935.358	16	20,683.4599	18,119.3946	0.00584
	Residual	1.142	1	1.1415		
	Total	330,936.500	17			
$Y_{\sigma_{res}}$	Model	450,438.4366	7	64,348.3481	46.84205	7.506×10^{-7}
	Residual	13,737.3034	10	1373.7303		
	Total	464,175.7400	17			
$Y_{\sigma_{-1}}$	Model	6531.77778	16	408.23611	90.71914	0.008231
	Residual	4.5	1	4.5		
	Total	6536.27778	17			

The critical values of the Student statistic (T), Fisher statistic (F), residual standard deviation (ResStDev), determination coefficient (R-sq), adjusted determination coefficient (Radj-sq) and predicted determination coefficient (Radj-sq (pred)) for the six models are shown in Table 9. The statistical data confirm the adequacy of the models. The probability of a coefficient being insignificant is $p > 0.05$. However, such coefficients are included in the models to minimise the residual (exp – model).

Table 9. Statistical data for the regression models.

Models	T	F	ResStDev	R-sq	Radj-sq	Radj-sq (Pred)
Y_{Ra}	12.70620	246.46392	0.000707	1.0	0.99995	0.99999
Y_{sk}	4.30265	19.42914	0.035152	0.99948	0.99560	0.98236
Y_{ku}	4.30265	19.42914	0.055152	0.99993	0.99938	0.99382
Y_{HV}	12.70620	246.46392	1.068400	1.0	0.99994	0.98755
$Y_{\sigma_{res}}$	2.22814	3.13546	37.064	0.97040	0.94969	0.88149
$Y_{\sigma_{-1}}$	12.70620	246.46392	2.1213	0.99931	0.9883	0.95594

3.4. Optimisations

3.4.1. Maximising Wear Resistance Under the Boundary Lubrication Condition

Sedlacek et al. [36] found that the combination of more negative skewness values and kurtosis greater than three improves wear behaviour under the boundary lubrication condition. This finding has been confirmed by other authors using sliding wear tests for different tribological pairs [40–42]. In addition, low average roughness R_a [43], increased surface microhardness [44] and surface residual compressive stresses [45,46] contribute to increased sliding friction wear resistance. Thus, the optimisation in this section is based on the well-known correlation between the finishing process, surface integrity and operating behaviour [47]. This integrated approach forms the basis of the modern field of surface engineering [48].

To find the governing factor values that maximise the sliding wear resistance of 42CrMo4 cylindrical parts under the boundary lubrication condition, the following multi-objective optimisation task was set. The vector of the objective functions is $\{Y(\{X\})\} = [Y_{Ra} \ Y_{Rsk} \ Y_{Rku} \ Y_{HV} \ Y_{\sigma_{res}}]^T$, where $\{X\} = [x_1 \ x_2 \ x_3 \ x_4 \ x_5]^T$ is the vector of the governing factors. The numerical vector $\{X\}^*$ must be found, for which $Y_{Ra}(\{X\}^*) \rightarrow \min$, $Y_{Rsk}(\{X\}^*) \rightarrow \min$, $Y_{Rku}(\{X\}^*) \rightarrow \max$, $Y_{HV}(\{X\}^*) \rightarrow \max$ and $Y_{\sigma_{res}}(\{X\}^*) \rightarrow \min$, where $\{X\}^* = [x_1^* \ x_2^* \ x_3^* \ x_4^* \ x_5^*]^T$ and $x_i^*, i = 1, 2, 3, 4, 5$ are the compromise optimal values of the governing factors. This task was solved by searching for the Pareto optimal solution approach using QStatLab and the NSGA II algorithm [49]. The following functional constraints were imposed: $0.05 < Y_{Ra} < 0.1 \mu m$, $Rsk_i < Y_{Rsk} < Rsk_j$, $Y_{Rku} > 3$, $HV_i < Y_{HV} < HV_j$ and $\sigma_{res_i} < Y_{\sigma_{res}} < \sigma_{res_j}$. The optimisation problem was solved iteratively, with the functional constraint intervals (Y_{Rsk} , Y_{HV} and $Y_{\sigma_{res}}$) reduced after each iteration to refine the resulting Pareto front, and the problem was further constrained by the fact that x_2^* and x_3^* can take only integer values (see Table 5). Figure 6 illustrates the final Pareto front containing 50 compromise optimal solutions.

The selected solution from the Pareto front is visualised in Figure 6, and its corresponding numerical values are shown in Table 10. To experimentally verify the compromise optimal values of the five SI characteristics, 20 samples were processed with the compromise optimal governing factor values shown in Table 10. The clustering centres of the obtained results are listed in Table 10 and show good agreement with the values predicted from the optimisation.

Table 10. Compromise optimal values (maximising wear resistance).

Compromise optimal values of the governing factors									
Coded (Dimensionless)					Natural (Physical)				
x_1^*	x_2^*	x_3^*	x_4^*	x_5^*	f_c^* , mm/rev	R^* , mm	r^* , mm	F_b^* , N	f^* , mm/rev
−1	−1	1	1	0.5424	0.05	0.4	4	150	0.0608
Compromise optimal values of the objective functions and experimental verification results									
Y_{Ra}^* , μm		Y_{Rsk}^*		Y_{Rku}^*		Y_{HV}^* , HV		$Y_{\sigma_{res}}^*$, MPa	
0.0763		−1.27		6.426		853.5		−980.5	
0.0691		−1.16		5.981		839.9		−958.3	

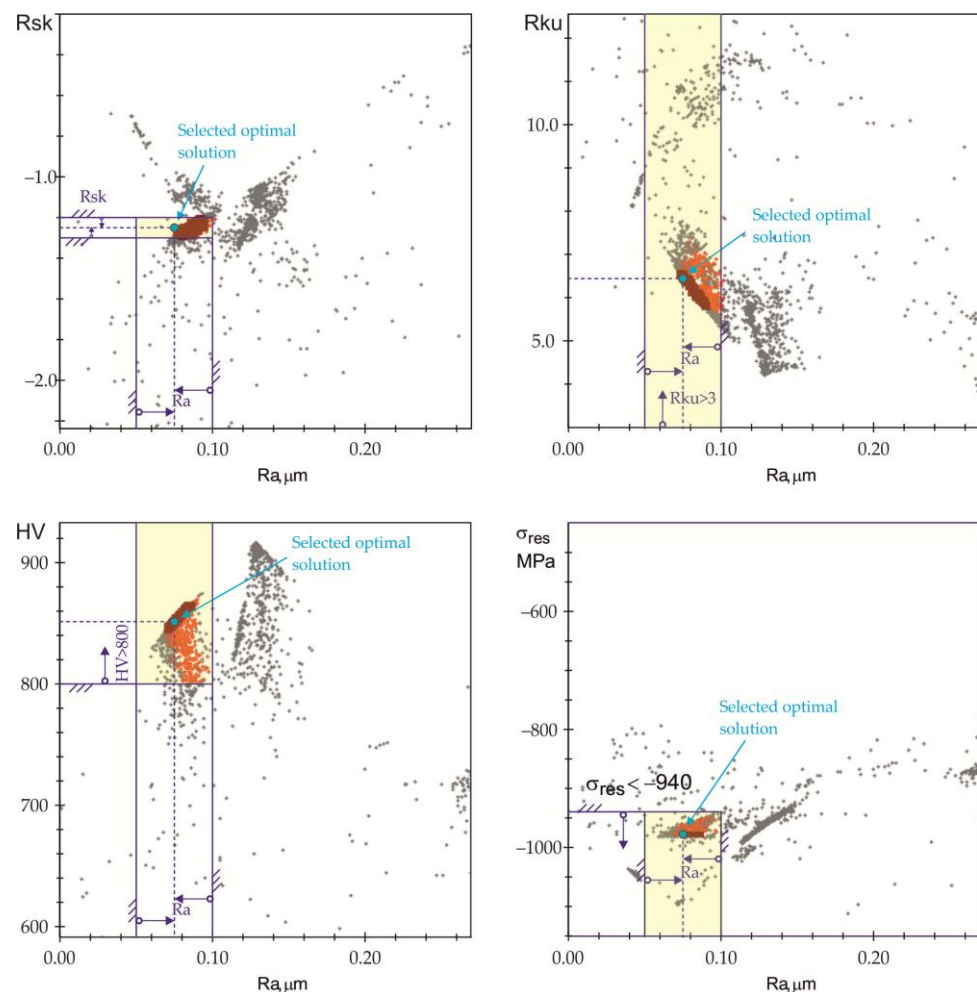


Figure 6. Generated Pareto front (maximising wear resistance under the boundary lubrication condition).

3.4.2. Maximising Fatigue Limit

A high fatigue limit is a basic requirement for heavily loaded axles and shafts. Increased microhardness and residual compressive stresses in the surface and closely located subsurface layers are known to improve a specimen's fatigue behaviour. However, regardless of the introduced residual compressive macrostresses, fatigue failure can start from the specimen surface if the finishing does not provide appropriate roughness parameters [39,50].

Figure 7 shows the effects of the governing factors on the fatigue limit obtained via ANOVA based on the experimental scheme (see Table 6). The maximum value of the fatigue limit is obtained when the cutting feed rate (x_1), burnishing force (x_4) and DB feed rate (x_5) are at lower levels, and the cutting insert radius (x_2) and diamond insert radius (x_3) are at higher levels. This combination of factor magnitudes corresponds to the seventh point of the experimental plan and yields a fatigue limit of 682 MPa. However, the experimental design is a fractional replicate and not all vertices of the hypercube are included; therefore, it is possible that there is a point in the factor hyperspace corresponding to a fatigue limit exceeding 682 MPa.

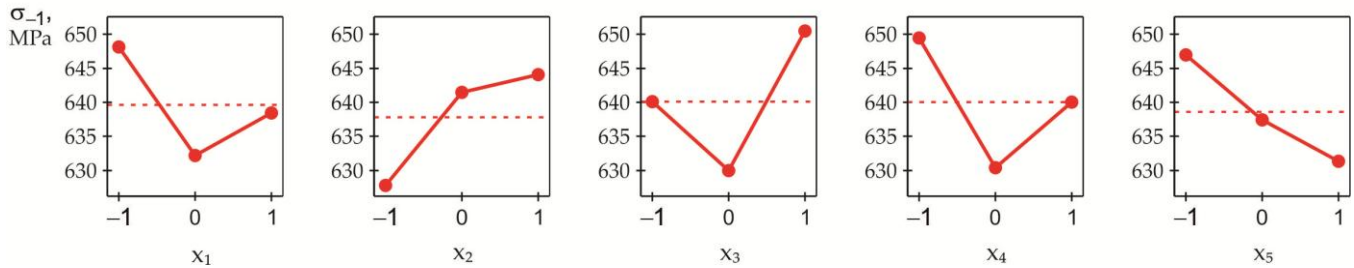


Figure 7. ANOVA of the main effects in the HCP (fatigue limit).

To find the governing factor values that maximise the fatigue limit of the heat-treated 42CrMo4 steel fatigue specimens, the following multi-objective optimisation task was set. The vector of the objective functions is $\{Y(\{X\})\} = [Y_{Ra} \ Y_{\sigma_{-1}}]^T$, where $\{X\} = [x_1 \ x_2 \ x_3 \ x_4 \ x_5]^T$ is the vector of the governing factors. The numerical vector $\{X\}^*$ must be found, for which $Y_{Ra}(\{X\}^*) \rightarrow \min$ and $Y_{\sigma_{-1}}(\{X\}^*) \rightarrow \max$, where $\{X\}^* = [x_1^* \ x_2^* \ x_3^* \ x_4^* \ x_5^*]^T$ and $x_i^*, i = 1, 2, 3, 4, 5$ are the compromise optimal values of the governing factors. In addition, the governing factors x_2 and x_3 vary discretely and therefore can only take integer values (i.e., -1, 0, or 1). Thus, the task was solved using the Pareto optimal solution approach and the SCAN method [37], satisfying the integer value requirement of x_2 and x_3 , using QStatLab. The following functional constraints were imposed: $0.1 < Y_{Ra} < 0.2 \mu\text{m}$ and $Y_{\sigma_{res}} > 682 \text{MPa}$.

Figure 8 illustrates the final Pareto front containing 12 compromise optimal solutions. The selected solution from the Pareto front is visualised in Figure 8, and its corresponding numerical values are shown in Table 11. To experimentally verify the compromise optimal values of the R_a roughness parameter and the fatigue limit, two groups comprising four specimens each (cylindrical and fatigued) were processed using the compromise optimal governing factor values listed in Table 11. The arithmetic mean values are listed in Table 11 and show good agreement with the values predicted by the optimisation.

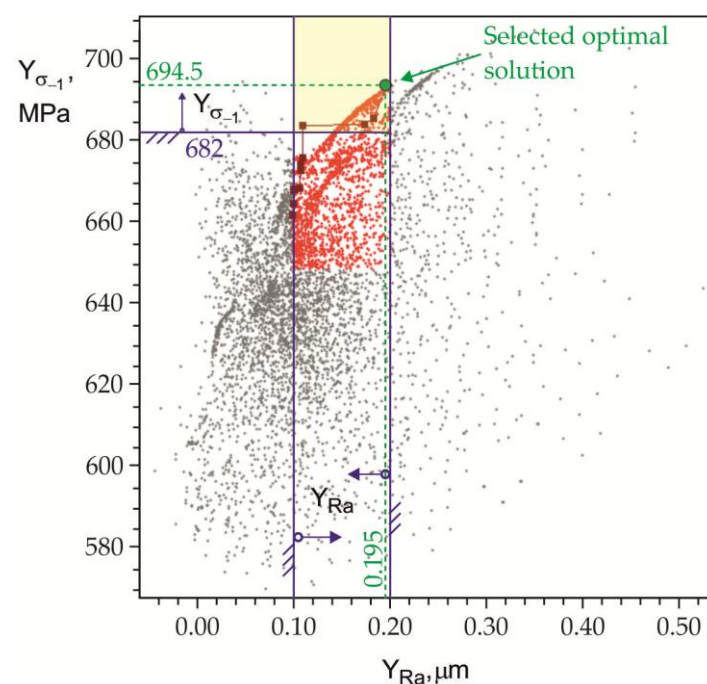


Figure 8. Generated Pareto front (maximising the fatigue limit).

Table 11. Compromise optimal values (maximising the fatigue limit).

Compromise Optimal Values of the Governing Factors									
Coded (Dimensionless)					Natural (Physical)				
x_1^*	x_2^*	x_3^*	x_4^*	x_5^*	f_c^* , mm/rev	R^* , mm	r^* , mm	F_b^* , N	f^* , mm/rev
−1	0	−1	−1	0.500	0.05	0.8	2	50	0.05
Compromise optimal values of the objective functions and experimental verification results									
Y_{Ra}^* , μm					$Y_{\sigma_{res}}^*$, MPa				
Optimisation		Verification			Optimisation		Verification		
0.195		0.118			694.5		689.7		

4. Conclusions

In this study, a sustainable advanced manufacturing technology based on HCP was developed for finishing heat-treated 42CrMo4 steel cylindrical parts using a holistic approach. The most important findings of this work are as follows:

- HCP, including cool-assisted dry hard turning and subsequent cool-assisted dry DB, was developed, studied and integrally optimised according to the criteria of maximum sliding wear resistance and maximum fatigue strength.
- When the main requirement is increased sliding wear resistance under the boundary lubrication condition, the HCP is optimised based on the correlation between SI and sliding wear behaviour. The compromise optimal values of the governing factors provide the following SI characteristics: average roughness $R_a = 0.0763 \mu\text{m}$, skewness $R_{sk} = -1.27$, kurtosis $R_{ku} = 6.426$, surface microhardness = 853.5 HV and surface residual stress = −980.5 MPa. The chosen parameter combination maximises the specimens' sliding wear resistance under the boundary lubrication condition.
- When the main requirement is maximum fatigue strength, the compromise optimal values of the governing factors provide a maximum fatigue limit of 695 MPa at an average roughness R_a of 0.195 μm .

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Abbreviations

ANOVA	Analysis of variance
CF	Cutting fluid
DB	Diamond burnishing
HCP	Hybrid combined process
NSGA	Non-dominated sorting genetic algorithm
SCW	Surface cold working
SI	Surface integrity

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