REVIEW

Mechanical and tribo-metallurgical behavior of 17-4 precipitation hardening stainless steel affected by severe cold plastic deformation: a comprehensive review article

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Abstract

This article comprehensively reviews the mechanical properties and tribo-metallurgical behavior of 17-4 precipitation hardening stainless steel (17-4PH SS) during and after cold plastic deformation. Referring to the scientific literature, stainless steels are one of the few types of ferrous alloys which could be appropriately set up through cold working processes in the forms of sheets or other shapes. Likewise, some other metal alloys such as mild low-carbon-based steels, copper and its alloys, aluminum alloys, and some others are the few types of metal alloys which have this capability. On the other hand, in engineering applications, there are several types of mechanical failures, which must be taken into account to investigate the mechanical behavior and tribo-metallurgical properties of any targeted materials. For example, corrosion resistance, wear resistance, and fatigue failure are investigated according to the microstructural studies, comprising of the grain size, grain boundaries, orientations, dislocations, and so on. Based on the published results, focusing on 17-4PH SS, one of the most main effective factors on mechanical and tribo-metallurgical performance is the grain size. Also, the favorable balance of two mechanical properties of strength and ductility has been reported as a dilemma in the materials science, and the problem delineates upon the limitations of numerous structural materials potentials. Following the failure analysis of the materials, in order to diminish the damages caused by fretting fatigue some methods such as ultrasonic processes are applied for the treatment of 17-4PH SS via changing the microstructure, residual stress, and other parameters. Also, through the other cold deformation technologies, the nanostructured surface layer with highly upgraded mechanical properties of several ultrasonic surface rolling process-treated 17-4PH SS has been obtained. To this end, such cold working processes on 17-4PH SS and their subsequent results are elaborated in this review paper.
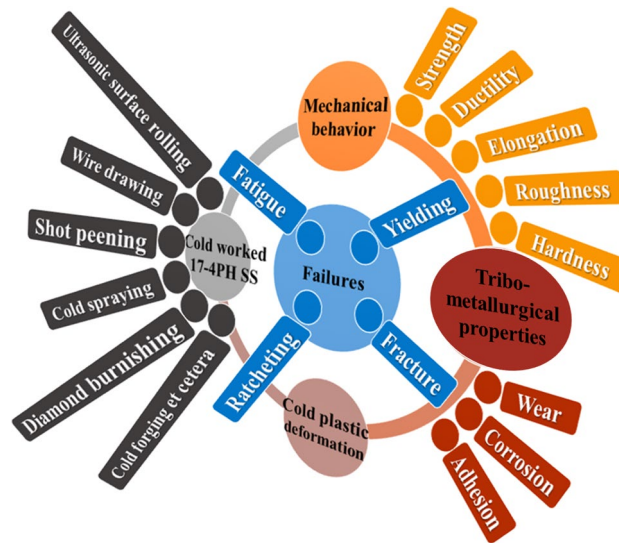
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Graphical abstract

Keywords Cold plastic deformation · 17-4PH stainless steel · Mechanical behavior · Tribo-metallurgical behavior

Abbreviations

1D	One dimensional
2D	Two dimensional
3D	Three dimensional
17-4PH SS	17-4 Precipitation hardening stainless steel
AM	Additive manufacturing
ARB	Accumulative roll bonding
BCC	Body center cube
CPD	Cold plastic deformation
CS	Cold spraying
DCR	Deep cold rolling
DSC	Differential scanning calorimetry
DSS	Duplex stainless steel
ECAP	Equal channel angular pressing
EDAX	Energy-dispersive X-ray analysis
EDXS	Energy-dispersive X-ray spectroscopy
FCC	Face center cube
FF	Fretting fatigue
FS	Friction surfacing
FTIR	Fourier transform infrared spectroscopy
HB	Brinell hardness
HCP	Hexagonal close packed
HPT	High-pressure torsion
HRC	Rockwell hardness
HT	Heat treatment
HV	Vickers hardness
MIM	Metal injection molding
MQL	Minimum quantity lubrication
NTWS	Nanotwinned structure
OM	Optical microscope
ODS	Oxide dispersion strengthened
PD	Plastic deformation
PF	Plain fatigue
SEM	Scanning electron microscopy
SPD	Severe plastic deformation
SP	Shot peening
TEM	Transmission electron microscopy
TRIP	Transformation-induced plasticity
TWIP	Twinning-induced plasticity
USR	Ultrasonic surface rolling
USRP	Ultrasonic surface rolling process
XRD	X-ray diffraction
YPE	Yield point elongation

Symbols

A	Area
b	The burgers vector amount of dislocation
C	The Cauchy component
D	The domain size
E	The energy
E_d	The dynamic energy which is equaled to the amplitude product of the dynamic load and the sinusoidal function of the vibration wave
E_s	The input static energy behind the ultrasonic head or the static energy overall value
E_t	The total energy
f	Friction factor
F	Load or force
F_d	The dynamic load
F_r	The reaction force

f_y	Nominal (MPa) (nominal steel yield strength)
g	The instrumental profile
G	The Gaussian component
h	The measured line profile
L	The mean domain size in the particular direction means the size of coherent scattering sections
P	Pressure
s	The structurally broadened profile
t	Time

Greeks

α	The phase material
β	The phase material
γ	The form of property of metal chemical element
δ	The form of property of metal chemical element
Δ	Variation or amplitude
ε	The strain
$\langle \varepsilon^2 \rangle^{\frac{1}{2}}$	The mean microstrain
$\Delta\varepsilon_t$	Total strain amplitude
θ	The angle between the incident X-ray beam and the diffracted direction
ρ	The density

Subscripts and superscripts

d	Dynamic
r	Reaction
s	Static
t	Total
y	Yield

1 Introduction

There has been always a growing demand for enhancement of the mechanical behavior of existing materials, addressing the industrial productions. To this end and as an effective approach, severe plastic deformation (SPD) is applied for metal forming and modifying required structures, by considering the fact that the typical industrial component productions are categorized into three sectors of mechanical forming, melting, and powder metallurgy. To be exact, cold working is defined as the metal forming process under recrystallization temperature, even at the ambient temperature range. In general, the four main classifications of cold working processes can be categorized as drawing (e.g., wire drawing, and sheet metal drawing), squeezing (e.g., rolling, forging, peening, riveting, and burnishing), bending (e.g., flanging, draw and compression, roll bending and forming), and shearing (e.g., sheet metal shear cutting, piercing, and so on).

On the other hand, the material type as well as its chemical, physical, and mechanical behavior define the performance of any component during and after its operation period. In this case, also the failure analysis, containing wear, overload, corrosion, and other consequences must be evaluated [38]. Indeed, during the last decade, studies about metal refinement in the microscale, defining as the grains smaller than 1 μm, by usage of the techniques of making SPD has been extensively noticed. Such materials have been considered as the new-born generation of the metal productions, which indicate outstanding physical and mechanical behavior in comparison with macroscale grain-sized materials. Severe plastic deformation is one of the most operational approaches to create micrograin metals. In comparison to the macrometals, much higher strength toughness as well as capability of ductility are observed in the micrometals. In addition, the growth of the surface mechanical behavior such as fatigue strength, hardness, and surface smoothness processes have been obtained with the SPD processes and for different materials [62, 68]. Moreover, equal channel angular pressing (ECAP)-twist extrusion, high-pressure torsion (HPT), and accumulative roll bonding (ARB) are some major severe plastic deformation processes. To cite the examples, Abbasi et al. [2] studied the ultrasonic peening process on the rolling mill roll graphite steel to augment the mechanical and thermal behavior. Moreover, Azushima et al. [6] reviewed the severe plastic deformation processes, where an ultra-large plastic strain has been enforced on a material to produce ultra-fine grained metal alloys. Valiev et al. [67] also investigated the nanostructured materials under SPD processes.

Based on Fig. 1, the overview of the current review paper following the standpoints of mechanical and tribo-metallurgic properties, cold plastic deformation, cold-worked 17-4PH SS, and the optimal enhanced factors, which is the concern of this article to be obtained.

On the other hand, steel as a typical ductile material is known to be cold-formed and used for cold plastic deformation (CPD) processes. 17-4 precipitation hardening (17-4PH) chromium–nickel–copper martensite stainless steel (SS), as an age-hardenable type of stainless steel, has high-grade mechanical properties and acceptable corrosion resistance in compared to the other types of stainless steels such as 18-8. In this regard, according to the final heat-treated microstructures, the precipitation hardening stainless steels could be categorized into three subfamilies, comprising of low-carbon martensitic (e.g., 17-4PH, 15-5PH, PH 13-8 Mo, and FV 520), semi-austenitic or austenitic–martensitic (e.g., 17-7PH and PH 15-7 Mo), and austenitic alloys (e.g., 17-10P). 17-4PH SS is also known as DIN EN 1.4542 or AISI 630 duplex material. Referring to present review paper, the classification of ferrous metal alloys, focusing on 17-4PH SS, is also represented in Fig. 2 as well.
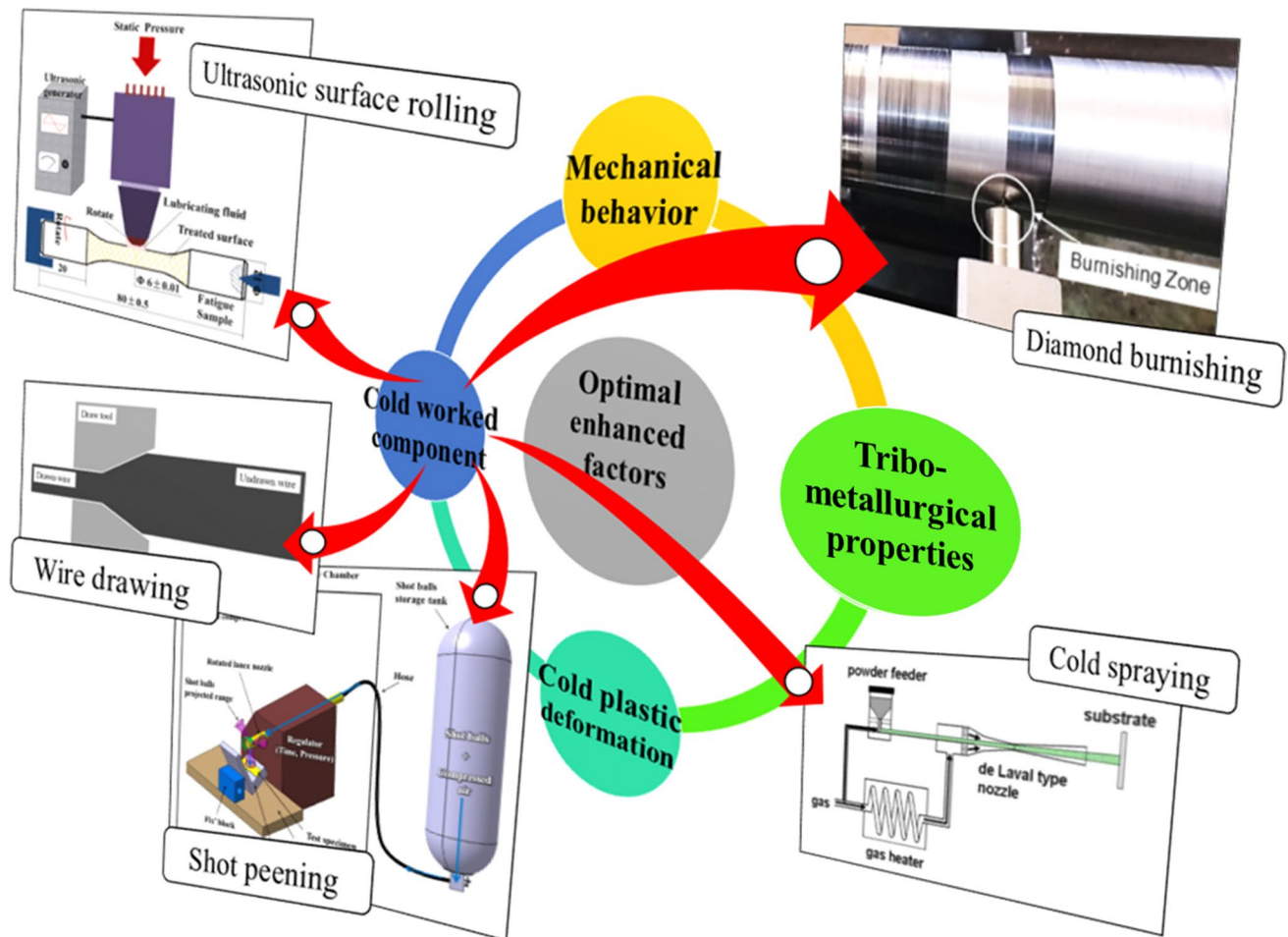
Fig. 1 The overview of the current review paper following the standpoints of mechanical and tribo-metallurgy properties of cold-worked 17-4PH stainless steels, focusing on cold plastic deformation phenomenon (Referring to the subfigures of different processes, including dry diamond burnishing process provided by Sachin et al. [55], the USRP indicated by Liu et al. [41, 43]shot peening process represented by Nam et al. [48], and cold spray by Schmidt et al. [56] (All subfigure are reprinted from aforementioned references, and with permission from Elsevier)

PH SS is defined as a low-carbon martensitic matrix, which could be strengthened by highly dispersed copper particles precipitation in the martensitic phase [52]. Martensitic PH SS possesses a predominantly austenitic matrix at the annealing temperatures, approximately of 1040–1065 °C while the cooling process to the room temperature engenders a transformation which modifies it to the martensite phase. In general, the aging condition is principally designated by 'H' tracked by the applied temperature at which the aging process occurs. 17-4 PH SS could be undergone heat treatments at different temperatures to enhance a vast range of mechanical and metallurgical properties. One-step aging heat treatment is a standard type applied to it (D0129). In some critical applications of such steels, 17-4PH can be utilized in the aged condition versus solution-treated one. The over-aged heat-treated condition can provide higher mechanical and tribo-metallurgical behavior such as

bulk-based durability or toughness and even more strong corrosion resistance in compared to the solution annealed heat treatment.

To be more exact, 17-4PH is basically applied for two conditions. H900 as peak-aged condition, which is heat-treated roughly at about 482 °C after solution heat treatment, and H1100 as over-aged condition, which is heat-treated at around 593 °C. In some literature, H900 type has represented as more inclined to embrittlement under particular working processes [17]. Subsequently, in the over H1100 condition, this material has been widely utilized in for the components which requires both high corrosion resistance and high strength [80] [71, 72]. For example, Isobe and Okabe [32] studied the kinetics of martensitic 17-4PH SS, and the retained austenite effects on the properties of over-aged materials. 17-4PH (Cr17Ni4Cu4Nb) is advanced by the source of Cr17 stainless steel. It typically comprises of
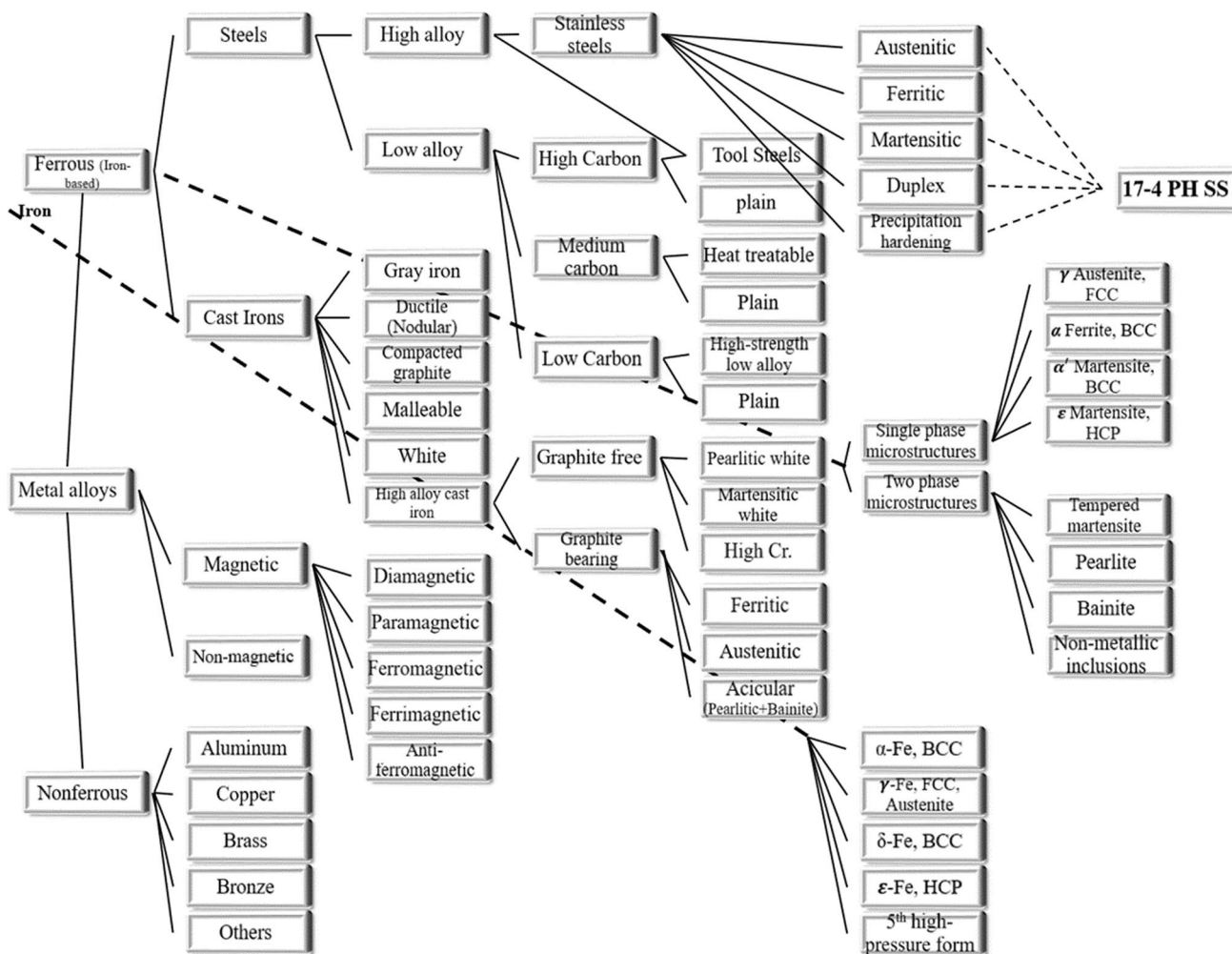
Fig. 2 The classified position of 17-4 PH SS among iron-based alloys

15.5–18.5 wt% Cr, and over adjusting the solution age treatment, 17-4PH could have desirable outstanding mechanical properties such as high strength, corrosion resistance, and ductility, causing to be an attractive choice through numerous types of applications and industries, namely automotive, medical equipment productions, nuclear mechanisms, aerospace, marine structures, power plants machineries, electronic products, and so on. For instance, an experimental research of mechanical failure of 17-4PH SS blades in a gas energy recovery turbine applications has been investigated by Liu et al. [45]. Also, Shen et al. [61] indicated the influence of solution-treated temperature approach on hydrogen embrittlement of 17-4 PH SS through valve production applications. Viswanathan et al. [69] have mentioned the microstructure properties and electrical resistivity of this alloy in some general aforementioned applications.

Moreover, the interconnected subject of cold working processes along with the heat treatment is another aspect of this field. In order to appraise the performance of 17-4PH

SS in hot and cold working temperature ranges, this steel would be easily forged in hot working temperatures; however, 17-4PH displays much higher deformation resistance as well as poor workability at cold working temperature processes referring to its high annealed hardness. As a result, in cold working temperatures, the over-aging process should be applied so many times for softening the material, which evidently causes higher costs of production hinted by Isogawa et al. [33]. As one of the cold working processes, diamond burnishing tools are designed to produce work-hardened, high quality, uniform finishes on various surfaces such as shafts, bores, and other industrial components by plastic deformation indicated by Sachin et al. [55].

Referrals to Davis [19] may profoundly help to clarify the theoretical subjects of microstructures, metallographic and tribological properties. Moreover, the microstructural analysis, heat treatment, as well as metalworking applications can be fundamentally investigated by referrals to Davis [20]. On the other hand, many field studies have

focused on various mechanical properties through various applications. Liu et al. [45] reported the failure behavior of turbine blade made of 17-4PH SS in a steelmaking factory. Or Liu et al. [41, 43] introduced a study about the fretting fatigue behavior of 17-4PH SS under ultrasonic surface rolling process. It is evident that there are also so many studies focusing on elevated temperature. For instance, Wang et al. [71, 72] introduced the microstructure evolution of 17-4PH SS over longstanding aging at higher temperature.

As the first step and in order to investigate the mechanical properties of 17-4PH SS, the significant point is to precisely recognize the overview of properties of any material based on Fig. 3; as a matter of fact, this definitely helps to draw a broader and more accurate definition at the first step.

2 Novelty of the study

As aforementioned remarks, severe plastic deformation is one of the most operational approaches to create micrograin metal alloys. Such materials have been considered as the new-born generation of the metal productions, which indicate outstanding physical and mechanical behavior in comparison with macroscale grain-sized materials. There are numerous review papers, which focus on different aspects of this field. However, in the current review article, mechanical and tribo-metallurgic properties of 17-4 precipitation hardening stainless steel during and after severe cold plastic deformation have been compiled that such comprehensive aspect can be rarely seen among literatures, considering other previous review studies so far. To monitor this claim,
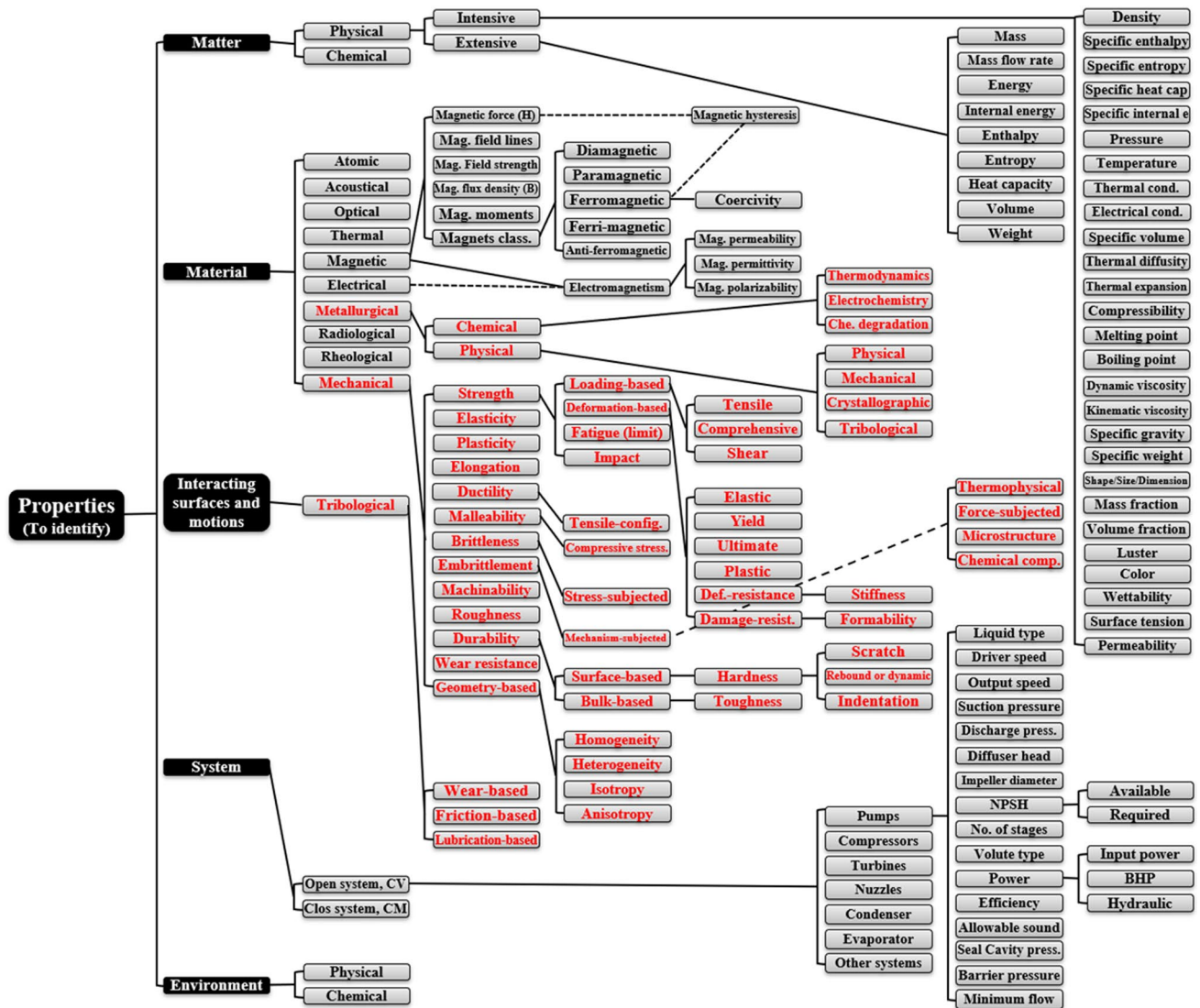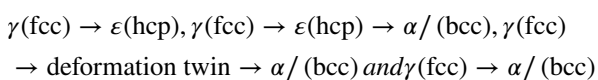
Fig. 3 Mechanical, metallurgical, and tribological properties of any material, concerning the current study; where do they fall in?

a glance over the previous related review papers has been carried out in this section.

Citing an example, Das [18] studied a comprehensive review of cyclic plasticity-induced transformation of austenitic SS via various experimental works, and the critical analysis of them. The formation micromechanisms of deformation-induced martensite such as ε (Hexagonal close packed (hcp)) and α/(Body center cubic (bcc)) are methodically tested by critical transmission electron microscope after cyclic PD of AISI 304LN austenitic SS at different total strain variations ($\Delta\varepsilon_t$) under environment condition. Based on the outcomes, while strain amplitude shows growth, the increase in extent of α/(bcc) martensite also observes. It is also reported that deformation-induced martensites could nucleate at a number of sites via mechanisms multiplicity with various sequences of transformation, as:

$$\gamma(\text{fcc}) \rightarrow \varepsilon(\text{hcp}), \gamma(\text{fcc}) \rightarrow \varepsilon(\text{hcp}) \rightarrow \alpha/(\text{bcc}), \gamma(\text{fcc})$$
$$\rightarrow \text{deformation twin} \rightarrow \alpha/(\text{bcc}) \, and \gamma(\text{fcc}) \rightarrow \alpha/(\text{bcc})$$

Based on their paper, such martensites could nucleate at a number of spots, including isolated shear bands, shear band intersections, shear band-grain boundary intersections, grain boundary triple junctions, dislocation piled-up, and so on anywhere total interaction energy helps to form. The proposed work quantitatively links also the formation strain amplitude dependency of the deformation-induced martensite as well as corresponding groups, and configurations of dislocation sub-structures. In another similar and comprehensive review in this field, Sohrabi et al. [63] reviewed the most recent advancement on the formation micromechanisms of deformation-induced martensitic as well as the reverse transformation. The outputs signify that the transformation of strain-induced martensitic could be a subject to control the microstructural and mechanical characteristics of metastable austenitic SS.

Some other review papers have been worked on the residual mechanical performance of various structural steels after to be exposed to fire heating or typically high elevated temperature ranges. Nevertheless, such observed fluctuating reports can be too particular and also are reasonably different from case by case. For example, Yu et al. [84] compiled postfire experimental data aimed at hot-rolled and cold-formed steels. They collected the statistical series of analyses upon the heating experience effects owing to the mechanical behavior of steels. The effectual mechanisms were enlightened as for the microstructure phase changes, interestingly during and after such high temperature exposure. Based on the literatures, the cold-formed steels show a higher level of effects through such phenomena due to the cold working dislocation release. Two sets of predictive analytical models for residual strength evaluation were calibrated, whereas those are mentioned highly universal and could be simply applied for such residual strength evaluation, regarding those two series of postfire hot-rolled and cold-formed steels. They referred to two main cooling techniques, which are normally assumed in the postfire investigations, namely CIA technique, stands for the cooling in air to simulate the condition of in which fire dying out naturally, as well as the cooling in water (CIW) one for simulation of a fire extinguished by water cannons. However, another method of cooling in blanket (CIB) is typically employed for studies of the cooling rate effect introduced by Hu et al. [29]. Table 1 denotes a summary of experimental data aimed at cold-formed steels.[1] Nominal steel yield strengthSuch studies on mechanical behavior of structural steels, again considering of exposure to the elevated temperatures, can be categorized into mild steel group and high strength steel (HSS). In this case and in another similar review study, Li et al. [39] reported the test experimental data upon mechanical behavior of hot-rolled carbon structural steels at such elevated temperatures, with strength grades of 235–960 MPa. They considered the effects of test method, manufacturing process of steels, loading and heating rates upon the structural steel performance. According to the literature results, for all different grades of steels, the nominal strength reduction factors (with 2.0% of strain) show downward trends. Though, such

Table 1 Summary of experimental data aimed at cold-formed steels reported by Yu et al. [84]

Steel type	Steel grade	Nominal f_y (MPa)[1]	Grade no.	Number of specimens	T (°C)	Cooling method
General strength cold-formed steel	Q235	235	–	20	300–800	CIA and/or CIW
	S35J2H	355	–	15	334–710	CIA
	G300	300	–	9	300–750	CIA
	G350	350	–	15	300–800	CIA
	G450	450	–	23	300–800	CIA
High strength cold-formed steel	G500	500	–	10	300–800	CIA
	G550	550	–	9	300–800	CIA
	Optim 700MH	700	–	27	200–1000	CIA
	Optim 900QH	900	–	14	200–1000	CIA

downward trends specifying the reduction factors indication of ultimate strength, Young's modulus, and 0.2% offset yield strength have differences with the different grades of steels.

Pursuing on the aforementioned subject, it is evident that the concept of cold and hot working of metal alloys is the initial subject to be clarified and is another difference of current review paper with such literature. In general, there is hot working process if the plastic deformation is done at the temperature range higher than the recrystallization temperature, which creates new grains, and it is cold working process when such physically manipulated deformation would be carried out under its recrystallization temperature, while, in cold working process, more energy is required for plastic deformation. In addition, a determinative item upon the grain refinement in terms of the various crystals and microstructures, defects, deformation, and annealing behavior is delineated based on the phases following the chemical elements. Citing an example, in the low-carbon steels, producing a lath martensitic structure delivers the effectual grain refinement because of the formation of blocks, packets, and laths. Besides, such structures can be compelling nucleation sites, which are required in the grain refinement. Consequently, during recrystallization annealing of the deformed martensitic matrix, the high dislocation density within laths is favorable to grain refinement. On the other side, the workability is significant to the grain refinement, which are according to the CPD, SPD, and recrystallization annealing of martensite structure [49].

Building upon all four main previously mentioned classifications of cold working processes, comprising of drawing, squeezing, bending, and shearing, the superplastic forming is basically implemented at hot working processes, and, there are only rare cases of obtaining superplasticity in nanostructured materials, which have been reported by some studies, namely [60] indicating a superplastic elongation up to 2000% in an $Al_9(CoCrFeMnNi)_{91}$ (at%) nanostructured-high-entropy alloy. In general, superplasticity is observed in materials which have very fine grains less than 10-µm size [60] and at low-scale strain rates, considering the high homologous temperatures bigger than half of the melting temperature that is referred to the hot working regime [47, 50].

In another related field, so many various steels are being processed by the techniques of additive manufacturing (AM). The various matrix microstructure modules and phases, namely austenite, ferrite, and martensite, as well as the different precipitation phases, namely intermetallic precipitates and carbides, have provided an enormous variability in the microstructure and behaviors to such series of alloys, like AM-produced steels. Nonetheless, steels would be subjected through AM-processing to time–temperature profiles, which are so dissimilar from the types faced with classical process routes, and, therefore,

the follow-on microstructures vary strongly accordingly. This contains a so much acceptable high-morphological and crystallographical textured microstructure owing to the high rates of solidification and non-equilibrium phases. For example, Bajaj et al. [8] reviewed on the various class of steels in fusion-based additive manufacturing (AM) processes. They presented the mechanical behavior, and corrosion properties, the microstructures, the heat treatments as well as the in-use applications. This consists of austenitic, duplex, martensitic and precipitation hardening stainless steels, TRIP/TWIP steels (transformation-induced plasticity (TRIP) and twinning-induced plasticity (TWIP)), maraging steel (strengthened by slow cooling and age hardening) and carbon-bearing tool steels and oxide dispersion strengthened (ODS) steels.

In some studies related to as-sprayed coating field, it has been found that some micro-sized grains and high dislocation density have been presented, which have been resulted from impact of high kinetic energy as well as SPD mentioned by Huang et al. [30]. In this regard, Sun et al. [64] worked on the recent advancement in various post-process treatments upon cold sprayed deposits (supersonic cold spray, or cold gas dynamic spray, or mostly called cold spray (CS)), containing heat treatment (HT), shot peening (SP), friction-stir processing, and laser re-melting. To this end, the effects of aforementioned post-treatments upon the microstructure, the residual stress, and mechanical behavior of CS deposits were reviewed.

In another field and as an approach for the enhancement of fatigue life is through surface residual stress inducement to hinder any crack initiation. Kumar et al. [35] worked on a review paper interestingly focusing on a microstructural investigation under different bulk, such as SPD, as well as surface mechanical treatments. Likewise, the effects of microstructural features, strain hardening, and residual stress on the mechanical behavior and fatigue crack mechanisms were studied. It was suggested that hybrid processes, including SP followed by deep cold rolling (DCR), can improve fatigue life. However, there is a noticeable point in this regard that lies in the relationship between the grains and cracking failure of the materials. To clarify, the high energy level of high-angle grain boundaries can permeate the crack occurrence while the low energy level of coincidence site lattice grain boundaries can prevent the cracks. In addition, the clarification of coarse grain microstructure can degrade crack-oriented fatigue life is quite important for further researches based on this gap among the studies. In other words, for understanding of microstructural role on fatigue life from quantitatively based standpoint, it would be vital to make clear the initiation and growth of microscopic fatigue crack [51]. According to the literature, the internal defects of materials, containing reversible traps (e.g., grain boundaries and dislocations) as well as the irreversible trap sites (e.g.,

inclusions, oxides, and carbides) due to various trap binding energy levels could be able to induce concentration of stress causing to crack initiation [14].

Overall, it is noticeable that the concept of the current review paper, focusing on the mechanical and tribo-metallurgic properties of 17-4 precipitation hardening stainless steel during and after severe cold plastic deformation could be a new review study with specific technical concern among all other previous related studies (Fig. 4).

3 A glance over the applications of 17-4PH stainless steels

The usages of all possible four previous-mentioned classifications of cold working methods are widely diverse, such as complex folded shapes, flat sheets, screw heads, screw threads, metal tubes, riveted joints, and so on. 17-4PH stainless steels are being utilized in a diversity of industrial applications, namely steam turbines (e.g., blades quality), biomedical instruments, chemical industry, marine industry, aircraft components, and power plants to substitute more expensive materials such as polymeric composite, titanium, and other alloys directed by Wang et al. [74, 75]. For another specific example, Bressan et al. [11] hinted the wear tribological failure in an industrial application of conveyor chain in the soya oil production. Such applications are followed by their outstanding combination of mechanical and tribo-metallurgic properties, e.g., investigation of corrosion resistance by Barroux et al. [9] as an example. To this end, such materials need to be technically served for a very long period of time within the entire life-span of a component. Therefore, the quality

Fig. 4 The overall concept of the present review paper

improvement of the surface, including wear resistance, surface hardness, and so on need to be attained. Below some overall limitations and advantages of cold working processes are elaborated, following the above-mentioned overview that also can be more generalized by referrals to [21]. In this regard, the investigation of commercial 17-4PH SS would be more noticeable as a study by Hsiao et al. [27]. Through commercial and industrial studies, Smith (2014), as Deringer-Ney corporation, suggested technical and cost advantages of cold-forming processes of precise components in the high-speed processes [22].

3.1 Advantages and disadvantages of cold-worked metal alloys, focusing on 17-4PH steels

As for the cold working disadvantages and limitations, the major factors can be delineated according to the literature as follows: first of all, only the small-sized metallic components could be easily set up under cold working while for the larger components, higher forces are needed. For example, the parts greater than 25 mm in diameter can be hardly rolled. Expensive and heavy monster machineries are required in case of large deforming forces. Secondly, the grain structures are not refined, and, moreover, the residual stresses show damaging effects upon particular properties of steels. The third type of limitations can be lie in the fact that numerous of the metals which have lower ductility, such as carbon steels or some alloy steels, could not be set up under cold working at room/standard temperature. Moreover, due to the high costs of required tools and equipment, such processes can be run when high volume of identical components quantities are required as for the production lines or the similar cases. However, by taking into account the aforementioned important remark, stainless steels are one of the few types of ferrous metal alloys which could be appropriately set up through cold working processes in the forms of sheets or other shapes. Some advantages of cold-worked metal alloys lead to put forward their usages preferably versus hot-worked ones [28]. Although hot working operation could nicely make changes on the shape and size of the metal component, the process arises at the cost of metal strength. Indeed, being exposure toward the heat technically causes to typically weaken the metal component. Consequently, cold working process is applied for the applications aimed at a robust finishing quality. Except the augmented strength offering by cold working processes, they are also easier to be performed. De facto, industries are able to operate cold working process much more quickly in compared to the hot working processes, considering processes needless heat. So, cold-worked metal alloys usually cost less for production. On the other hand, cold working processes lead in ductility loss as well as augmentation of hardness and strength of steel. However, the surface finish quality is enhanced, and also adjacent tolerances could be maintained. There are also
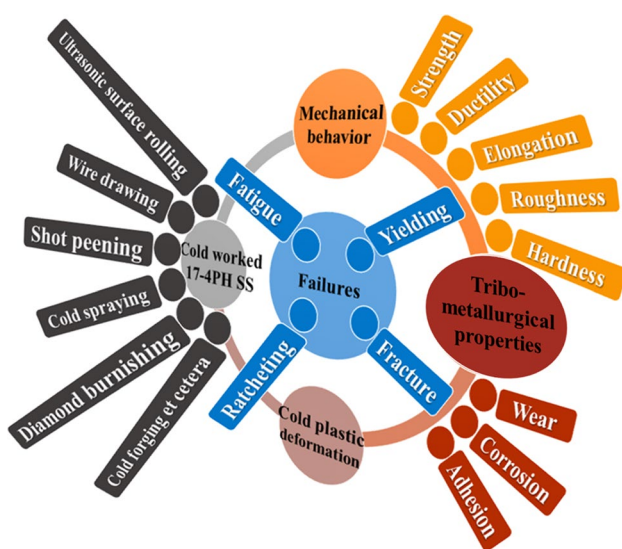
specific outcomes based on different types of the cold working processes, which would be discussed in the next parts. For instance, shot peening can be assumed as one of the promising treatment processes aimed at providing great compressive residual stresses as well as surface hardness [59]. To cite another example, Al-Obaid [3] suggested shot peening as an effective process in retarding stress corrosion in stainless steel materials. In another general point of view, Lang et al. (2003) reported the residual stresses and fatigue behavior of low, medium, and high-strength steels. Building upon the above-mentioned facts, the overall advantages and/or disadvantages of cold working processes versus hot-worked processes have been also gathered by (https://www.mech4study.com/2016/06/difference-between-cold-working-and-hot-working.html).

4 Mathematical background

As the various approaches which are broadly applied for efficient upgrading of the mechanical behavior of materials in their microstructural characteristics, in the ultrasonic cold deformation technology, as one of the common cold deformation processes, a substantial modification can arise in the mechanical properties of the material such as surface hardness and smoothness from the flattening of surfaces (Fig. 5).

In this case, Eq. (1) shows the total energy, E_t, which is required for the UCFT process;

$$E_t = E_s + E_d \tag{1}$$

where E_s and E_d indicate the input static energy behind the ultrasonic head or the static energy overall value, and the dynamic energy (Eq. (2)), which is equaled to the amplitude product of the dynamic load, F_d, and the sinusoidal function of the vibration wave, respectively.

$$E_d = F_d \mathrm{Sin}\,(2\pi ft) \tag{2}$$

As a typical mechanism, a pneumatic system is considered in order to avoid backlash on the return stroke by the tool which tolerates the reaction force. To measure the experimental reaction force, the pressure (P) which
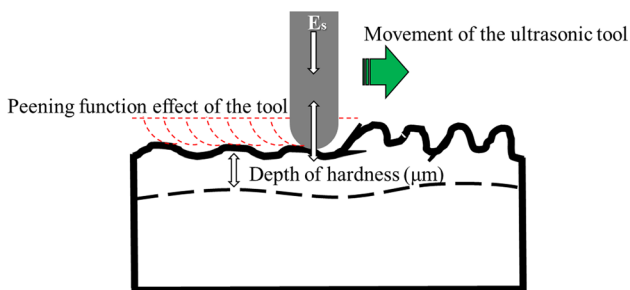

Fig. 5 Peening function of the ultrasonic tool illustrated by Abbasi et al. [1] (Redrawn by referring to the work by Abbasi et al. [1]

is applied by the air compressor behind the piston is multiplied by the area of piston (A) following Eq. (3);

$$F_r = PA \tag{3}$$

Hence, the reaction force is neutralized by the designed pneumatic mechanism.

Shot peening process is another type of cold working processes that is utilized for the mechanical behavior modification and inducing a compressive residual stress layer (or superficial compressive stress) of different types of metal alloys. The shot peening effect upon microstructure of 17-4PH steels has been studied by different researchers. For instance, Wang et al. [74, 75] studied the microstructure strengthening affected by shot peeing upon laser hardened 17-4PH steel by usage of X-ray diffraction (XRD) profiles. The XRD profiles of different specimens have been done by diffractometer of Dmax/rc with CuKα radiation, current of 100 mA, and 40 kV voltage. Based on the study by Langford [36], Voigt approach was used to calculate the microstrain of the deformation layer, and the study of Williamson and Smallman [78] was employed for the dislocation density. According to Voigt method, the integral breath relationship is as follows:

$$\beta_G^{h2} = \beta_G^{s2} + \beta_G^{g2} \tag{4}$$

$$\beta_C^h = \beta_C^s + \beta_C^g$$

where β indicates the microstructure phase material, subscript G shows the Gaussian component, subscript C denotes the Cauchy component, superscript h signifies the measured line profile, superscript s represents the structurally broadened profile, superscript g denotes the instrumental profile.

It is considered that the Cauchy component of the structurally broadened profile is exclusively because of the crystallite size, and also the Gaussian component is aroused from microstrain. The microstrain, ε, as well as the domain size, D, in Voigt method are as follows:

$$\varepsilon = \frac{\beta_G^s}{4\tan(\theta)} \tag{5}$$

$$D = \frac{\lambda}{\beta_C^s \cos(\theta)}$$

θ denotes the angle between the incident X-ray beam and the diffracted direction.

The inconstant structural scale of particular peak would reflect the microstructure modification in such diffraction direction of crystal plane. By usage of more peaks, the calculation of the domain size and microstrain can help to achieve wider information in more details about

microstructure in the various plane diffraction directions. The diffraction profile measurements can be accomplished by the iterative electrolytical removal of thin surface layers as well as the subsequent XRD measurements. To this end, the microstrain as well as the domain size can be acquired through Eqs. (4) and (5). Next, for the dislocation density calculation, the equation among the dislocation density, domain size, and microstrain can be according given by [78]:

$$\rho_t = \frac{2\sqrt{3}}{b} \frac{\left\langle \varepsilon^2 \right\rangle^{\frac{1}{2}}}{L} \tag{6}$$

where ρ_t indicates the total dislocation density, b shows the burgers vector amount of dislocation, $\left\langle \varepsilon^2 \right\rangle^{\frac{1}{2}}$ is the mean microstrain, L represents the mean domain size in the particular direction mean the size of coherent scattering sections.

5 Effectual improvement of the mechanical behavior on the microstructural characteristics

Referring to the study by [1], different methods have been extensively applied for efficient improvement of the mechanical behavior of materials via morphological modification aspect in their microstructural characteristics. In this review study, the main focus would be on the investigation and enhancement of mechanical and tribo-metallurgic properties of 17-4PH stainless steel; however, in order to appraise the overall outlook, some comparisons are made between 17-4PH and some other related materials. On the other hand, it is quite determinative that the relationship between mechanical behavior and the microstructural analysis of materials can be challenging based on the identification of microstructures. In this regard, the characterization of the grain sizes, grain boundaries, grain orientations, phase distribution, nucleation of new formed grains in different heat-treated conditions, dislocation density along with other possible phenomenon can define mechanical and tribo-metallurgical behavior.

5.1 Mechanical properties of 17-4PH stainless steel

As one of the cold working processes, diamond burnishing process produces work-hardened, high quality, uniform finishes on various surfaces such as shafts, bores, and so on, by plastic deformation. For instance, Sachin et al. [55] presented a study about the diamond burnishing behavior on surface integrity of 17-4PH stainless steel under cryogenic condition, minimum quantity lubrication (MQL) and in dry

environments to investigate the surface integrity characteristics, including residual stresses and microhardness. Burnishing depth, speed, feed, and number of passes were the chosen parameters to be considered. According to the results, maximum microhardness was achieved under cryogenic, MQL, and dry environment by the amounts of 395 HV, 369 HV, and 357 HV, respectively. Moreover, the maximum residual stress, respectively, for cryogenic, MQL, and dry environment were observed as follows -352 MPa, -282 MPa, and -195 MPa.

Wu et al. [79] mentioned 17-4PH stainless steel is used as one of the most commonly materials in metal injection molding (MIM) processes. Chung and Tzeng [16] studied the artificial aging impact on the mechanical properties and microstructure of MIM of 17-4PH (which typically comprises of 3–5% copper) at different temperatures. According to the results, the microstructure of the as-sintered MIM 17-4PH is chiefly comprised of lath martensite type, δ-ferrite, plus nodular SiO_2 inclusions. The influence of precipitation hardening would be to fortify the MIM 17-4PH by the precipitation of numerous fine spherical ε-Cu phases on the lath martensite matrix that efficiently block the dislocations movement. As for the increase in aging temperature upper than 480 °C, the ε-Cu phase would grow coarser which causes in MIM 17-4PH over-aging and reduces the hardness.

There are other cold deformation technologies to engender a nanostructured surface layer, at nano-scaled microstructures, with highly upgraded mechanical properties of 17-4PH stainless steel. Such enhanced nanofuture-based effects on mechanical properties can be induced by varied processes. Also, different promising approaches on different SPD nanostructured materials are being continuously reported. For example, Bagherifard et al. [7] indicated that the increased kinetic energy of shot peening induced remarkable nanoscale grain refinement on the top layer of magnesium alloy caused to enhance the surface roughness and microhardness.

Ultrasonic burnishing process is another promising technology. In general, the burnishing processes can be categorized into three fundamental groups, containing ball, roller, and slide burnishing methods according to the tool type, and three typical types of vibratory, sonic or normal, and ultrasonic burnishing processes based on the oscillation frequency indicated by Zhang [88]. In addition, and following the above-mentioned approaches, the ultrasonic surface rolling (USR) process, as a new modern technology, is conducted as a combination of the ultrasonic frequency vibrations and static forces, as well as the benefits of ultrasonic impact treatment (UIT), surface mechanical rolling treatment (SMAT), and low plasticity burnishing (LPB), referring to Ye et al. [82], the study of ultrasonic nano-crystalized surface modification on microstructural properties

of a stainless steel, or the other studies compared to the stainless steels, such as the work by Zhang and Lindemann [86], defining the relation of roller burnishing and the high-cycle process of fatigue performance, or another research by Wang et al. [76] focusing on the effects of such process on microstructural behavior of a type of titanium alloy. These processes make materials with superior surfaces while considerably enhance the wear resistance, fatigue resistance, and fretting fatigue resistance. For instance, Wang et al. [70] experimentally enhanced the surface property of austenitic stainless steel by using electropulsing-assisted USR process. Or Zhang et al. [87] report demonstrated that the surface properties of 17-4PH SS, including hardness, roughness, wear and corrosion resistance, were drastically modified based on USR-treated process. In another comparison point of view between stainless steels and other materials, Liu et al. [40] has studied the effect of the USR process on fretting fatigue of Ti-6Al-4 V alloy. The resulting enhanced fatigue behavior largely contributes to the compressive residual stresses, which can effactually suppress crack initiation caused by fretting fatigue. Liu et al. [41, 43] studied a gradient structured surface layer fabricated on 17-4PH SS specimens by utilization of a USR process in order to reduce the fatigue failure via changing the microstructure, microhardness, surface roughness, and residual stress. Indeed, ultrasonic processes are taken into account as one of the techniques to address a surface modification. To cite another example, Zhang et al. [87] reported the surface properties enhancement of USR-treated 17-4PH SS by obtaining a particular thickness deformation layer, which was consisted of the nano-sized metal grains on the surface of steel. This improvement was determined by the variations of microhardness, surface roughness, and the residual compressive stress. For example, the roughness was considerably mitigated and the microhardness of surface was improved by 20% compared to the initial situation. In order to evaluate the nanostructured surface layer quality of USR-treated 17-4 PH SS, two tests of potentiodynamic polarization and friction-wear performance were conducted. According to the results, and from tribological and mechanical failure point of view (Fig. 6), both corrosion and wear resistance were augmented by such experiments. Plain and fretting fatigues are two significant mechanical failure modes in the engineering systems, which largely arise from the surface/sub-surface of metallic components. In this regard, Pandey et al. [66] took a look at grain refinements by ultrasonic surface shot peening to enhance the resistance against fatigue crack initiation. Schönbauer et al. [58] also studied the cyclic frequency on the torsional fatigue of 17-5PH SS. In a related similar study, Liu et al. [41, 43] represented the influence of USR process on plain fatigue (PF), fretting fatigue (FF), and surface integrity behaviors of 17-4PH SS. Based on the results, USR processing times showed a momentous effect on the PF

and FF of 17-4PH SS. Most importantly, enhanced PF life subsequent from USR process demonstrated much higher in compared to the FF life in case of the mechanism variations of PF and FF. One approach for the enhancement of fatigue life is through surface residual stress inducement to hinder any crack initiation. To this end, several studies have focused on the effects of microstructural features, strain hardening, and residual stress on the mechanical behavior and fatigue crack mechanisms. Similar interconnected works, say Alnaj-jar [4], also indicated the microstructures of selective laser melting-based 17-4 PH SS aimed at corrosion behavior. Eshkabilov et al. [24] have worked on another similar investigation focused on 316L stainless steel.

In comparison with the above studies on 17-4 PH SS under such technology of the ultrasonic processes, there are other studies working on other materials, which can demonstrate the potential of these processes causing the highly upgraded mechanical properties of the material surface. Hukki and Va Laakso [31] utilized the ultrasonic burnishing process on 34CrNiMo6-M tempering steel, and, consequently, the residual stresses and surface roughness were enhanced by approximately 90% and 400%, respectively. Also, Bozdana et al. [10] employed the ultrasonic deep cold process in order to augment the service life as well as the surface behavior of Ti6Al4V parts. Indeed, ultrasonic cold technologies are utilized to increase material surface characteristics, e.g., the hardness and smoothness improvement (or decrease in roughness) by the tool frequent striking through a reciprocating type of motion, referring to the study by Abbasi et al. [1].

Also, Abbasi et al. [1] studied the ultrasonic cold forging technology (UCFT) as for developments of surface mechanical behavior of cold-worked alloy steel tool (6XB2C). Through a simulation study, the accurate geometrical contours of a set of the UCFT tools were gained. In addition, a pneumatic mechanism was designed by the simulated UCFT to provide the static load as well as the avoidance for the tool backlash through the retracting motion. The mechanical tests of the post-UCFT process exposed an enhanced hardness value by the amount of 17% (with 150 mm depth) as well as an augmented smoothness property in the range of 0.6–0.132 mm in the compressed surface layers. In this research, the ABAQUS commercial software has been employed to simulate the 2D UCFT process. Various advantages of ABAQUS including user-friendliness, accurate analysis, high-speed simulation, and powerful modeling make it logic to be chosen. This is while the ANSYS commercial software was also used to define a modal analysis of the geometrical dimensions of both booster and the horn components. One of the strategies for enhancing the surface hardness of 17-4PH SS is the deposition of it on the AISI 304 substrate through friction surfacing. Guo et al. [25] indicated that severe plastic deformation (PD) in friction surfacing
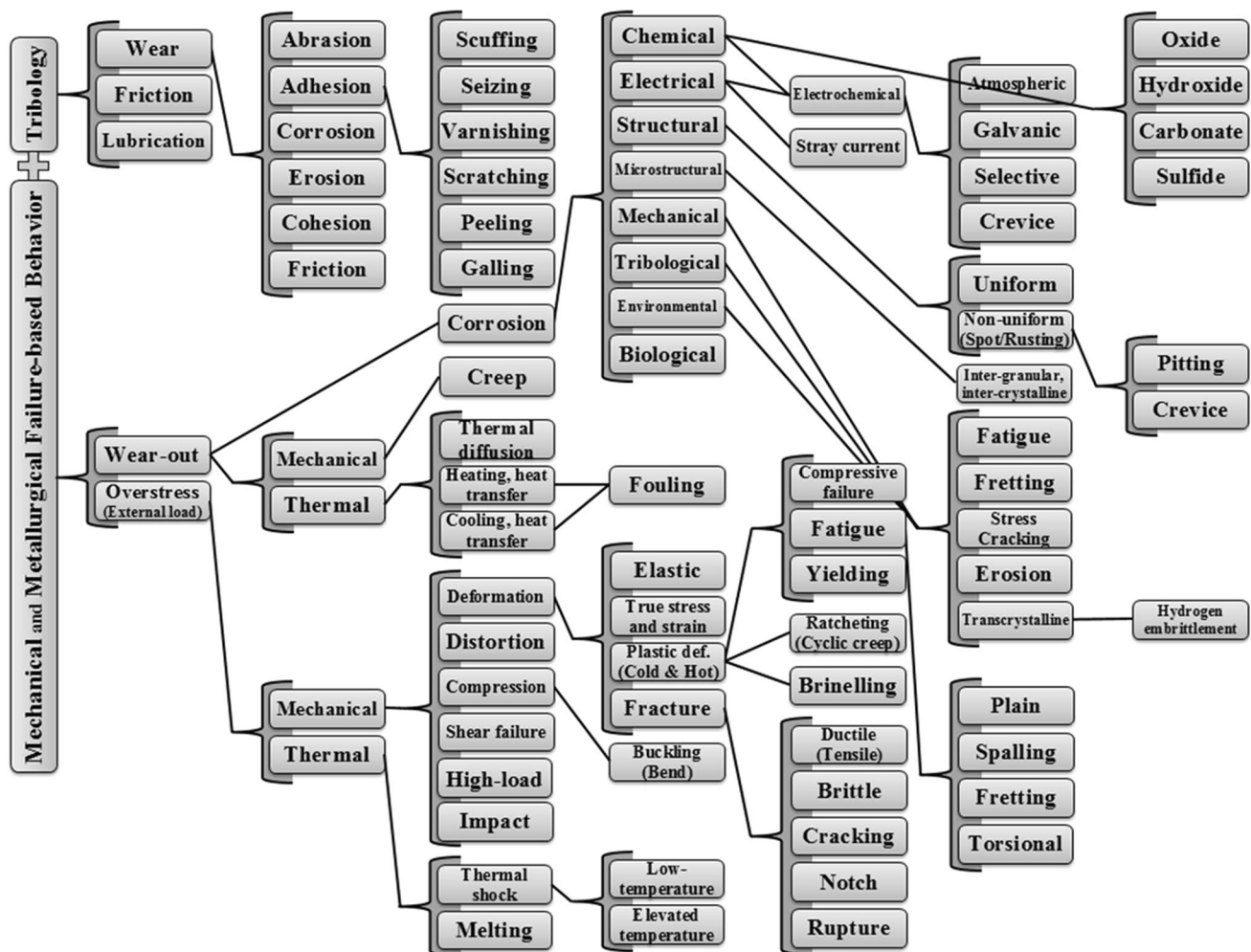
Fig. 6 Mechanical failure analysis overview (The failure possibility of metal-alloy components arises from the degradation mechanisms)

(FS) causes the strain incompatibility, which induces the formation of Cr-rich, means Ni and Cu-depleted composition, δ-ferrite of 1.8–2.7% along the plastic flow direction with stress concentration. Augmentation in hardness of the friction-surfacing-based coating was chiefly ascribed to the high dislocation density led by severe PD. Lashgari et al. [37] studied the influence of various process parameters, namely build orientation (vertical versus horizontal), scanning pattern (hexagonal versus concentric), single and double scan upon the microstructure and tribological properties (corrosion and wear resistance) of 17-4PH SS via material characterization methods, referring to Table 2, including X-ray diffraction (XRD), scanning electron microscopy (SEM), and electron back scatter diffraction (EBSD).

Following the above-mentioned concept, and referring to the effect of microstructural features upon the mechanical and tribo-metallurgic properties of stainless steels, one of the most key factors that can directly influence mechanical performance is the grain size. For instance, regarding fatigue failure as one of the tribological factors, in the short crack of the fatigue process, the vital barrier against the crack growth is the grain boundaries in steels. Citing an example of crack growth studies, Cao et al. [12] referred the cracks initiation from intergranular micro-cracks level on the surface toward the depth of S45C carbon steel. Trško et al. [65] investigated the ultrahigh cycle fatigue regime of low-alloy steel, 50CrMo4, under shot peening process. For other materials and as another comparison references, say alloy 718, the positive effect of nanostructured surface layer on fatigue life has been studied by Anand Kumar et al. [5], and the enhanced fretting fatigue and crack initiation performance of ASTM Grade 5 has been evaluated by Yang et al. [81].

There are so many studies such as Hong et al. [26] using two methods of crack density and dimensional analysis for assessment of the effects of grain-boundary resistance and grain size upon short crack regime as well as fatigue life of five groups of stainless steels. The output of study indicated that the fatigue life increased with

Table 2 Metallic material characterization as the part of metallographic techniques

Advanced material characterization techniques	Targeted item to be characterized
Optical microscope (OM)	Microstructures, or the structural and crystallographic analysis (typically as a non-destructive test)
Scanning electron microscopy (SEM)	Surface morphology, microanalysis, phase identification, and failure analysis (typically as a non-destructive test)
X-ray diffraction (XRD)	The structural composition/features or the structures of crystalline materials to identify the nature of the metallurgical phases. XRD is also the best precise approach to measure residual stress of either exceptionally strained points or the surfaces of moving parts (typically as a non-destructive test)
Energy dispersive X-ray spectroscopy (EDXS)	Similar to XRD to characterize the elemental composition or chemical distribution, specifically to identify the precipitates (typically as a non-destructive test)
Electron back scatter diffraction (EBSD)	For the phase distribution, colourful texture map of phases, and the microstructural or crystallographic analysis, grain sizes and orientations (typically as a non-destructive test)
Transmission electron microscopy (TEM)	Higher microstructural characterization, specifically to observe thin specimens including tissue sections, identification of the precipitates, the density dislocations, the molecules, and so on (typically as a non-destructive test)
Differential scanning calorimetry (DSC) analysis	The texture characteristics, microstructural properties (as a thermoanalytical technique)

a reduction in grain size. Also, Kumar et al. [35] reported (with main focusing on fatigue crack mechanism) that in order to concurrently attain an acceptable set of strength and ductility properties, gradient microstructure, that is to say, nanocrystalline on the surface a well as coarse in core could be created in the materials by means of surface mechanical treatments. Indeed, and following the aforesaid study, the desirable balancing of strength and ductility has been always an old dilemma in the materials science, and the problem lies in the limitations of numerous structural materials potentials, specifically different classes of steels.

5.1.1 Different techniques conducted to evaluate the mechanical properties

As shown in Table 3, different types of tests are conducted to evaluate the mechanical properties of the targeted materials that here the focus is evidently on 17-4PH stainless steel. Citing some examples, Liu et al. [44] study shows that the measurement of the machined surface hardness was carried out by the NanoTest Vantage equipment from the UK, considering a load of 500 mN as well as Vickers hardness testing device from China, considering the load of 9.8 N. Although the microhardness measurement as well as the half-peak width (called as FWHM) from the XRD experiments are the well-known approaches for testing the

Table 3 Different types of tests (examinations) conducted to evaluate the mechanical and tribo-metallurgy properties

Tests (examinations)	Evaluated item
Tensile test	The tensile strength, elongation, ultimate tensile strength, yield strength, and so on
Fatigue test	Life time analysis of components
Bending test	The fluting intensity value
Torsion test	The maximum torque, torsional shear stress, shear modulus, material's breaking angle, or the interface between two materials
Friction-wear performance potentiodynamic polarization	Nanostructured surface layer quality (e.g., USR-treated 17-4 PH SS)
Hardness test	The hardness
Roughness test	The roughness
Fracture toughness test	Determination of the energy required for initiation of failure in a material
Three-point bending fatigue life test by employing a servo-hydraulic fatigue tester	Fatigue
Electrochemical examination	The mechanical and tribological failures (e.g., corrosion)
Corrosion test (e.g., salt spray test)	Resistance to corrosion
Wear track and surface analysis	Tribological behavior
Metallographic examination	The microstructures, the grain size, the distribution of grains, and phases analysis

machined surface hardness. Also, a servo-hydraulic fatigue tester equipment, Instron 8801, from the USA, was applied for the tests of three-point bending fatigue life examination. In another research, Barroux et al. [9] performed electrochemical experiments to analyze the corrosion in the martensitic 17-4PH stainless steel. After such electrochemical examinations, the corroded surfaces of material were also observed using optical microscope (OM) and SEM techniques for analysis of the corrosion failure. The surface roughness measurements were done after those stages. Zebarjadi Sar et al. [85] mentioned several tests to assess the mechanical behavior of one type of low-carbon steels through warm rolling process. A differential scanning calorimetry (DSC) analysis was used to determine the texture characteristics or microstructural properties. This experiment was carried out by reheating up the specimens to 1060 °C and then cooling to standard room temperature range. Moreover, a bending test was done to investigate the fluting intensity value. In order to determine the tensile strength and yield point elongation (YPE) of the samples, they were examined by the tensile test at room temperature and at a crosshead displacement rate of 2 mm/min. Also, for the investigation of the steel texture, the electron backscattered diffraction (EBSD) method was utilized in various thermomechanical conditions.

5.2 Mechanical behavior during and after cold plastic deformation

Shot peening process is one kind of cold working processes associated with plastic deformation that is used to modify the mechanical behavior and induce a compressive residual stress layer (or superficial compressive stress) of different types of metal alloys. It consists in striking a surface with shot or projectiles, e.g., metals, ceramic particles, or glass, at a high speed rate acted similar to a mini-hammer, with adequate force to produce PD. According to a paper by Wang et al. [74, 75], shot peening and dual shot peening treatments have been implemented upon laser hardened 17-4PH SS with different specimens headed for enhancement of the 17-4PH steel fatigue life after laser hardening treatment. As a result, the fatigue life improved substantially after shot peening treatment. The changes of characteristics of hardness, roughness, and residual stress distribution were debated to attain the effect of shot peening on laser hardened 17-4PH SS (Fig. 7). Based on the results, the initial residual stresses did not show any effect upon the distribution of final residual stress in shot peening treated area. Through the different stages of shot peening, employing the small diameter projectiles reduces the roughness of specimens. Moreover, a hardness augmentation has been generally found in the surfaces after such treatment of shot peening as a result of grain size refinement, high compressive residual stresses,
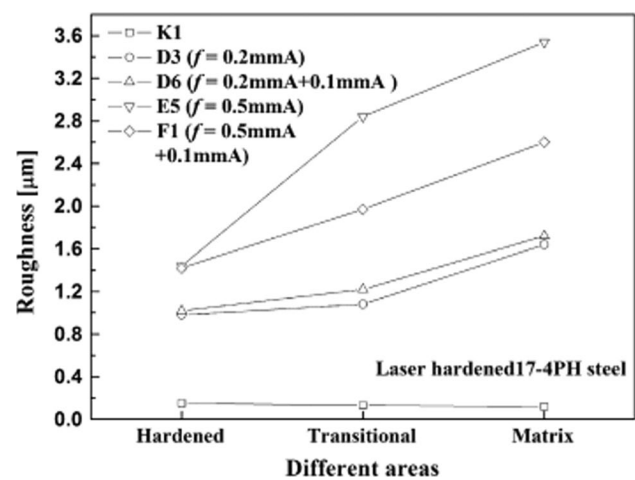

Fig. 7 Effect of shot peening and dual shot peening processes upon roughness in various areas reported by Wang et al. [74, 75] (Reprinted from Wang et al. [74, 75] and with permission from Elsevier)

and growth of microstrain alongside the dislocation density in those of areas. Following the aforementioned paper, in another research, the microstructural analysis of laser hardened 17-4PH SS after shot peening process was investigated by Wang et al. [73]. Based on the results, the shot peening treatment removed the retained austenite derived by manufacturing process and increased the surface hardness of the specimens. In comparison with 17-4PH SS studies, the microstructural investigations of other materials under shot peening process are widely being implemented. Jamalian et al. [34] studied the microstructural advancement of a gradient microstructure formed through a severe shot peening procedure in AZ31 magnesium alloy during isochronal and isothermal heat treatment. They mentioned the start of recrystallization was at 150 °C from the surface while continued over the thickness up to the appearance of newly formed defect-free structure with relative stability considering slow grain growth at the range of 300–450 °C temperature and through all layers deformed.

Flow forming process is a kind of cold-forming process, which make certain that the controlled properties of the final component have been set with no distortion. Maj et al. [46] analyzed martensitic 17-4 PH SS after the process of flow forming using four various strains alongside with subsequent standard-based heat treatment. Based on the outputs, a higher strain caused to display an overall higher strength as well as the structure refinement, albeit to the elongation shaped. The precipitation process was influenced by high deformation, and also the grain boundaries ratio was considerably increased. Strain hardening contributed to an increment in the steel strength,even though, such effect reduced after heat treatment. In addition, and based on the dense forest dislocations, the path length of dislocation was not

free that considerably caused to augment the plastic resistance plus hinder grain refining. Consequently, the residual stress also would be comparatively low (Fig. 8). So, high deformations of 17-4PH SS can be achieved by flow forming process, though the mechanical properties did not change noticeably due to the dominant mechanism of precipitation hardening.

Ultrasonic surface rolling as the other cold deformation technologies engenders a nanostructured surface layer with highly upgraded mechanical properties of 17-4PH stainless steel. The deformation mechanism as well as the mechanical properties of several USRP-treated metal alloys, such as 17-4PH SS, are being widely studied. Taking the examples of USRP-treated 17-4PH SS, initially shaped elongated ultra-fine grains have been refined through dislocation glide represented by Liu et al. [42]. For instance, Zhang et al. [87] investigated a deformation layer forming on the surface of such a USRP-treated 17-4PH SS (considering a specified thickness and while composed of nanoscale grains). After such USRP treatment, and based on the reported results, the corrosion resistance property of the steel was remarkably

increased. In order to investigate the mechanical behavior after cold plastic deformation processes and to cite some examples of several other materials after CPD, Cherif et al. [15] employed the ultrasonic nanocrystal surface modification (UNSM) on austenitic (Gamma) steel AISI 304 to demonstrate the compressive residual stresses as well as the outstanding strain hardening behavior after the process. Ren et al. [53] mentioned the improved surface and microstructure evolution of cold-worked die steel, Cr12MoV, under USRP and deep cryogenic treatment.

Cold spraying (CS) or cold gas dynamic spraying is assumed as one of the recent deposition procedure, comprising of impacting a high-speed stream array of solid particles onto an objective substrate, in which the deposition could be successful if impact velocity is beyond a threshold rate (the critical velocity), studied by Schmidt et al. [57]. This relies on the particle size, the substrates, mechanical and thermo-physical properties, such as density, melting point, yield strength, and specific heat, plus the relevant temperatures indicated by Yu et al. [83]. Dosta et al. [23] experimentally and numerically represented the
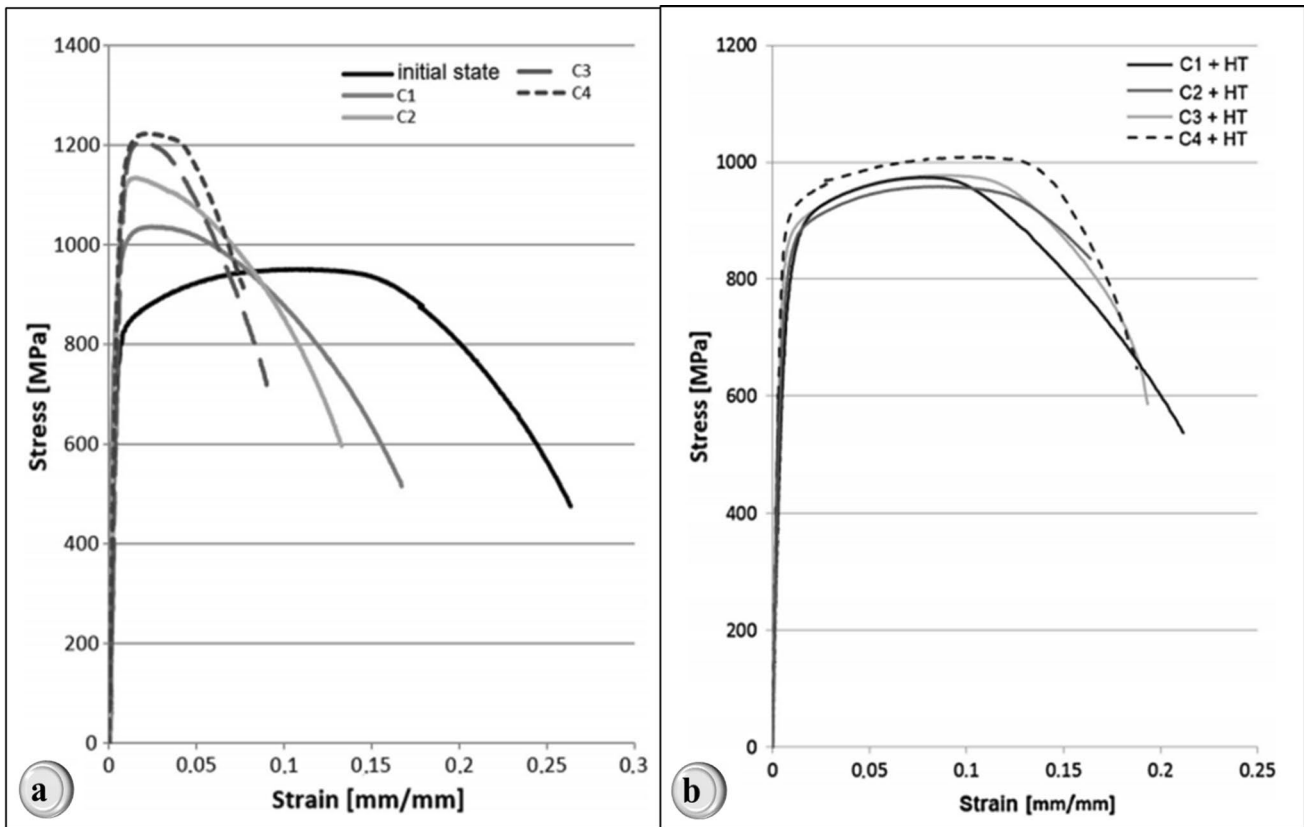

Fig. 8 **a** Tensile tests; cold-formed specimens, **b** Tensile tests; cold-deformed specimens after heat treatment represented by Maj et al. [46] (Reprinted from Maj et al. [46], and with permission from Springer)

PD phenomenon in ductile substrates of aluminum alloy (Al7075) and low-carbon steel (AISI A570Gr36) during CS deposition of WC–Co. A 3D finite element modeling by using the explicit computational methodology via Abaqus software was employed to simulate the impact of WC–Co particles CS toward ductile substrates. According to this work, the particle adhesion of CS WC–Co onto above-mentioned ductile metal substrates was largely indicated because of high-rate and adiabatic PD of the substrate that caused to metal jetting. This process was confined from the substrate surface and as the amount of a few micrometers, in which temperature increased so rapidly leading to weaken the material, and plastic strain concentration. Beneath that zone, the mechanical behavior and microstructure of the substrate stayed unchanged, with no measurable strain hardening or recrystallization.

In another standpoint, the desirable balancing of strength and ductility has been always an old dilemma in the materials science, and the problem lies in the limitations of numerous structural materials potentials, specifically different classes of steels. For instance, Wei et al. [77] specified a tactic of increasing the strength of TWIP steel, considering at no ductility desirable balancing. By putting on torsion to cylindrical TWIP steel specimens to make a structure of gradient nanotwinned (NTW) alongside the radial direction. It was found that the yielding strength of steel could be doubled, considering at no decrease in ductility, moreover, the evasion reason of strength and ductility balancing follows the gradient hierarchical NTW structure (NTWS) formation during pre-torsion as well as the subsequent tensile deformation. Different runs of finite element analysis (FEA) simulations according to crystal plasticity were carried out to find out the reason of the gradient twin structure leads both strengthening as well as ductility retention, and also in what way sequential torsion and tension cause to the perceived hierarchical NTWS via activation of various twinning structures.

In terms of the simulation studies, there are numerous articles based on either commercial software such as Ansys, Abaqus, et cetera or in-house coding software such as Matlab, Arduino, Python et cetera that can be followed by the concept of machine learning and deep learning approaches to predict the possibility of any failure during or after cold working to optimize the manufacturing processes to decrease the failure rate. For instance, as for the implementation of classification and clustering algorithms, Ruiz et al. [54] used the *K*-Nearest Neighbors (KNN), Random Forests, and Artificial Neural Networks algorithms for classification. The study showed that the heats, considering a greater possibility of undergoing any failure during wire drawing of steel, were detected and, consequently, caused to enhance the product final quality. *K*-means clustering was effectively utilized to identify the

manufacturing remarks lessening the probability of failure during the whole process. Based on the clustering analysis results, the heat rate undergoing failure can be decreased in the order of 2.5 times.

6 Discussion

As already elaborated in the above-previous parts, and referring to the four main general classifications of cold working processes, comprising of drawing, squeezing, bending, and shearing, the following discussion is deduced. Cold-worked 17-4 precipitation hardening stainless steels can be considered as one of the promising and unique research subjects among the related fields. Moreover, 17-4PH could have desirable outstanding mechanical properties such as high strength, corrosion resistance, and ductility, causing to be an attractive choice through numerous types of applications and industries elaborated in this paper.

To this end, the overall evaluation of various processes and their effects are compiled in this section. By flow forming process as one of the cold working processes, and through one of the analysis of martensitic 17-4 PH SS after the process of cold flow forming Maj et al. [46], a maximum of thickness reduction of martensitic 17-4 PH SS (after standard-based heat treatment) up to 67% could to be achieved with an acceptable surface finishing and without any cracks (Fig. 9).

According to Fig. 10a, by the cryogenic diamond burnishing process the enhanced surface integrity is achieved. However, the gradual decrease in microhardness of lamellae is observed by the deeper surface layer. Also, Figs. 10b and 9c illustrate that after shot peening, as another cold-worked process and in a role of an efficient treatment process, the increased surface hardness is obtained. Moreover, the microstructure analysis of laser hardened 17-4PH SS after shot peening shows the elimination of retained austenite microstructure phase derived by the manufacturing process. Retarding of stress corrosion cracking after shot peening is another advantage of this processes. Likewise, Fig. 10d indicates that the decrease in fatigue failure is expected by the application of USR process via changing surface roughness and hardness, microstructures, and residual stresses.

As aforementioned discussion in this paper, in order to investigate the cold plastic deformation, there are several mechanical behavior factors, namely fatigue (e.g., plain, pitting, spalling, and fretting), compressive failure, yielding, ratcheting, or cyclic creep, and so on, to be studied on 17-4PH stainless steels as for comprehensive true research. Regarding the mechanical behavior, tensile strength enhancement of the cold drawn 17-4PH steel materials

Fig. 9 Analysis flowchart of 17-4 PH steel after the process of cold flow forming
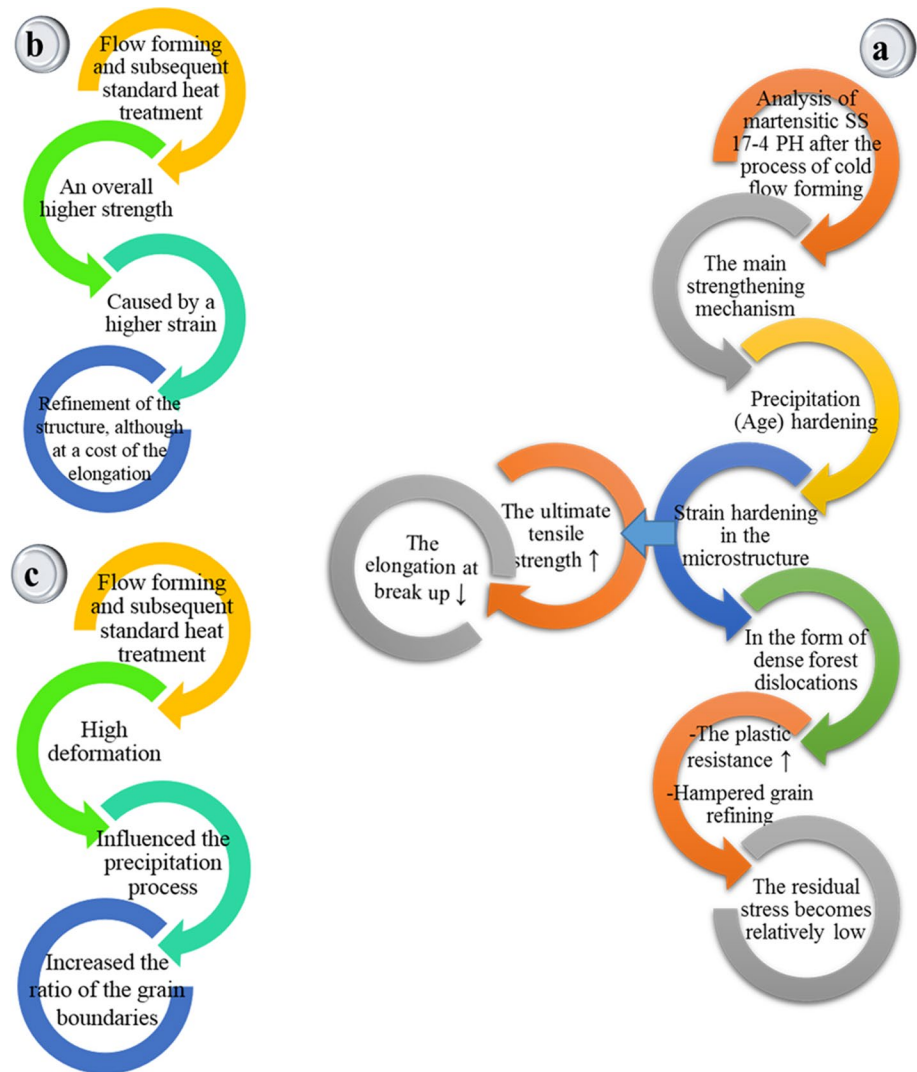
reduces the growth rate of crack under the cyclic loading. USR process integrated with deep cryogenic treatment has demonstrated an advancement versus conventional USR process in surface mechanical properties enhancement, such as lower surface roughness as well as smoother machined surface considering fewer probable failures and cracks. Literature also reports that microstructure analysis of shot peening upon laser hardened 17-4PH SS can decrease damages on surface while can increase the resistance against the surface crack initiation, as another aspect of enhancement in mechanical properties. This process introduces compressive residual stresses on the surface to make an obstacle versus the initiation and/or growth of micro-cracks. Cold-worked processes also cause increment in ultimate tensile strength, as well as fatigue strength, on the other hand, it causes to reduce resistance against corrosion failure. Moreover, cold working process helps to generate both the internal stresses and residual stresses.

On the other hand, for various modes of failure, a series of optimal factors typically exist that enable to enhance fatigue life. Scholars have revealed that the gradient nanocrystalline structure induced by SPD can noticeably increase the wear resistance of surface as well as the anti-fatigue performance. In this case, in order to investigate the mechanical behavior such as fatigue, several effects of microstructural features, strain hardening, residual stress, and other parameters are required to be taken into account accordingly. For instance, referring to residual stress, it is come up and remained in steel; unless, the residual stresses are eliminated by later heat treatment. Once reheating process is implemented under the crystallization temperature range, they are eliminated without considerable variation in physical behavior of the grain structures. The influence of cold working process is removed by further heating treatment into the recrystallized range and causes to restore the steel to its original status. Moreover, temperature range of recrystallization for steel is elevated. Regarding the effect of microstructural features
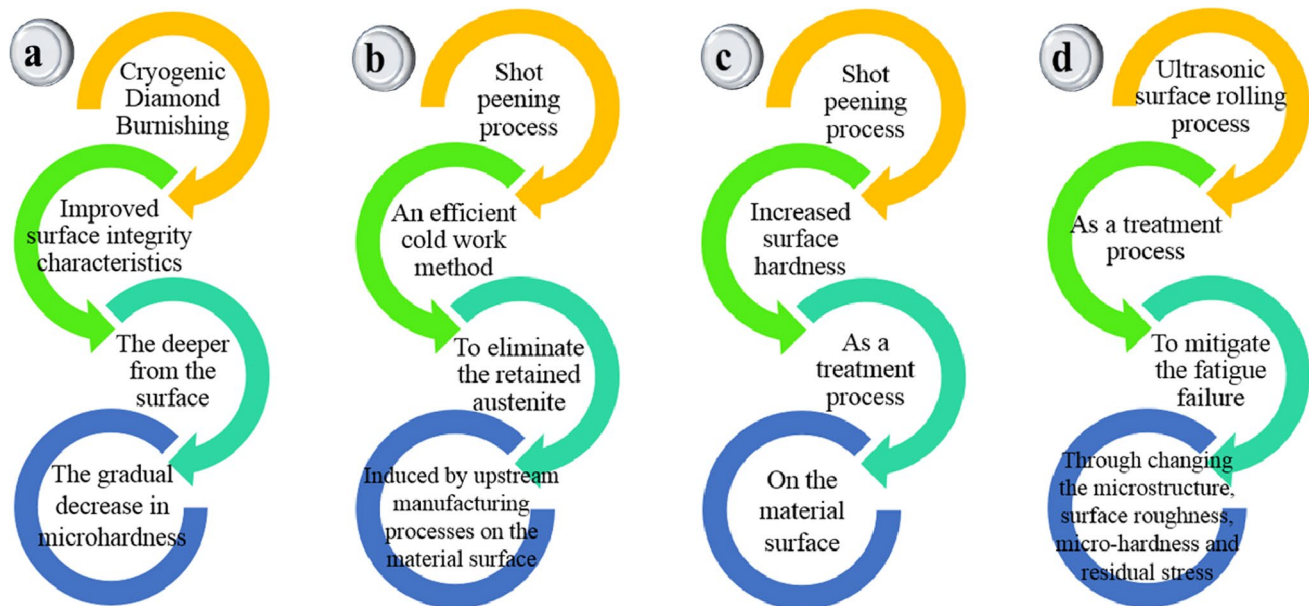
Fig. 10 Analysis flowchart of 17-4 PH steel after the cold-worked processes of **a** diamond burnishing, **b** and **c** shot peening, as well as **d** ultrasonic surface rolling

upon mechanical and tribo-metallurgic properties of stainless steels, one of the most key factors that can directly influence mechanical performance is the grain size. Noteworthy progresses have been so far accomplished over the recent decades in the processing metals for optimization of their properties. Introducing twins as the second-level structures in grains is one of the current examples in this field provided by Wei et al. [77]. Although such investigations have extensively improved the nanostructured materials science, a big question still remains on scaling up the structures to huge structural engineering materials in the wide-ranging industrial demands. Referring to the fact that cold working processes lead in ductility loss as well as augmentation of hardness and strength of steel, indeed, such philosophy of nanotwinned structures beside the grain size gradient for advancement of strength and ductility together, some approaches for improvement of the TWIP steel strength via a linearly graded NTWS have been introduced as well.

6.1 17-4PH position level among other comparable materials

Stainless steel material as a group of iron-based alloys generally shows high-grade mechanical properties and acceptable wear and corrosion resistance; however, it is significant to recognize these properties and behavior level as well. To clarify, experimental and numerical studies demonstrated that the metal matrix composites such as Al/diamond composites had superior wear and corrosion resistance behavior in comparison with the 17-4PH alloys or the selective laser

meting Inconel 625 indicated by Chen et al. [13]. The metal matrix composites are defined as the composite categories consisted of at least two parts, one necessarily part of a metal plus another various metal or even another different material, namely an organic compound or a ceramic and so on. For instance, Chen et al. [13] reported the influential role of the diamond reinforcement in enhancement of the wear resistance onto pure Al substrates.

7 Conclusion and future outlook

Steels, as typical ductile materials, are recognized to be also cold-formed and used for cold plastic deformation processes. To this end, the mechanical and tribo-metallurgy properties of iron-based alloys, focusing on 17-4PH steel, have been reviewed in this article.

- As one of the cold working processes, the cold flow forming has been indicated for a good obtainable thickness reduction with an acceptable surface finishing and without any cracks.
- Shot peening process treatments are employed to modify the mechanical properties of metal alloys. Such modifications contain surface hardness, surface roughness, and surface residual stresses that have noticeable effects upon the fatigue life of different components. Following the reported literature, modifying the surface of laser hardened 17-4PH SS materials can cause to enhance the

fatigue life, decrease the surface roughness, and increase in hardness which lie in the grain size refinement, high compressive residual stresses, and growth of microstrain alongside the dislocation density.

- Diamond burnishing tools, as another method of the cold working processes, are designed to produce work-hardened, high quality, uniform finishes on various surfaces such as shafts, bores, and so on, by PD.
- Ultrasonic surface rolling-treated approach, as one of the common cold-worked ultrasonic deformation technologies, is taken into account to engender a nanostructured surface layer with substantial modification in mechanical properties of 17-4PH stainless steel. Higher corrosion resistance and higher resistance against fatigues life are two of such highly upgraded properties. Based on the results, the analysis of microstructures of iron-base alloys implies that the δ-ferrite content, as one of the single-phase constituents, evidently improved in the ultrasonic surface rolling-treated specimens.

It is evident that through different cold working-based manufacturing processes, namely diamond burnishing, cold spraying, cold rolling, cold forging, ultrasonic cold deformation technology, and other cold working technologies, different microstructure formation are produced. Here, some general effects and influential outcomes of cold working processes on metal alloys, with concentration on 17-4PH steels, are as follows:

- Concerning the effect of microstructural features upon mechanical and/or tribo-metallurgic properties of stainless steels (focusing on 17-4PH SS), one of the most key factors that can directly influence mechanical performance is the grain size.
- The desirable balancing of two mechanical properties of strength and ductility has been always an old dilemma in the materials science, and the problem lies in the limitations of numerous structural materials potentials, specifically different classes of steels.
- As a future work, through an analysis of martensitic 17-4 PH SS by the process of cold flow forming and with subsequent standard-based heat treatment, the similar microstructures were reported for specimens that behaved independence of the thickness reductions. As for the standpoint of future applications, the additional stress caused by the PD did not affect the precipitation process. The resultant residual stress was fairly low, and to some extent the microstructure was only distorted that specified susceptibility to PD.

The analysis of microstructures of iron-base alloys (carbon steels, alloy steels, cast irons, tool steels, as well as stainless steels) specified that the δ-ferrite content, as one of the single-phase constituents, evidently improved in the USRP-treated specimens that the cause and effect of which can be elaborated in more detail in the future studies Liu et al. [41, 43].

Declarations

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