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Variability of Residual Stresses and Superposition Effect in Multipass Grinding of High-Carbon High-Chromium Steel

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The distribution of residual stresses (RS) and surface integrity generated in heat treatment and subsequent multipass grinding was investigated in this experimental study to examine the source of variability and the nature of the interactions of the experimental factors. A nested experimental design was implemented to (a) compare the sources of the RS variability, (b) to examine RS distribution and tensile peak location due to experimental factors, and (c) to analyze the superposition relationship in the RS distribution due to multipass grinding technique. To characterize the material responses, several techniques were used, including microstructural analysis, hardness-toughness and roughness examinations, and retained austenite and RS measurements using x-ray diffraction. The causality of the RS was explained through the strong correlation of the surface integrity characteristics and RS patterns. The main sources of variation were the depth of the RS distribution and the multipass grinding technique. The grinding effect on the RS was statistically significant; however, it was mostly predetermined by the preexisting RS induced in heat treatment. Regardless of the preceding treatments, the effect of the multipass grinding technique exhibited similar RS patterns, which suggests the existence of the superposition relationship and orthogonal memory between the passes of the grinding operation.

Keywords multipass grinding, residual stress, surface integrity, tool steel, x-ray diffraction

1. Introduction

1.1 Variability of Residual Stresses

Residual stresses (RS) are defined as stresses that exist in a material without any applied external force. They are usually generated by thermal and transformational stresses as a result of heating, cooling, and mechanical working processes (Ref 1). The basic assumption of this study was that for an adequate description of the RS behavior, the experimental design methodology must be comprehensive enough to analyze the underlying variance structure. Generally, a stochastic element is embodied, even in the deterministic approach, which delineates the property of the material by eliminating all aspects of uncertainty in the process. Under such a deterministic approach, the experimental treatments are treated as if they were fully determined, and a model is available that predicts the RS or other properties of the material of interest with complex configurations. At a practical level, in industrial operations the RS are compared with some tolerance values obtained by dividing their ultimate levels by a "safety factor," so as to yield a level above that of the failure limit. This industrial practice recognizes random features of the RS distribution in the material (Ref 2) and should be investigated further to improve the present knowledge on the theoretical aspects on the nature of the RS variability, contributing to better control of the manufacturing process.

Because RS can alter cyclic deformation forces and either accelerate or decelerate crack propagation of a part in service, it is imperative to understand the origin of the RS and their characteristic distribution to optimize the parameters of the manufacturing processes used in the preparation of the part and, thus, to reduce functional uncertainties. The latter would allow one to control and predict the service behavior of the part, which in the long run will help to delay mechanical property degradation and prolong its fatigue life. Arguably, no two samples, even if they have been subjected to the same manufacturing process, would have identical properties; as such, it is impossible to investigate RS behavior without resorting to experimental design methodology.

1.2 Effect of Heat Treatment and Grinding

The specific aim of this study was to investigate the effect of final surface finishing by grinding on surface integrity and RS generation of differently heat-treated, high-carbon, high-chromium, cold-worked steel. The selection of the material was motivated by the existing failure-related problems (i.e., spalling and crumbling) when used for dies in thread-rolling applications (Ref 3). Surface finishing by grinding enhances surface quality and enables dies with lower average distortions. Often being a final operation in the dies preparation cycle, the properties induced in grinding directly affect failure-related material characteristics. One of the most effective ways of increasing fatigue performance is through achieving a favorable combination of compressive and tensile RS embedded in the material before service. Theoretically, RS patterns may be ef-

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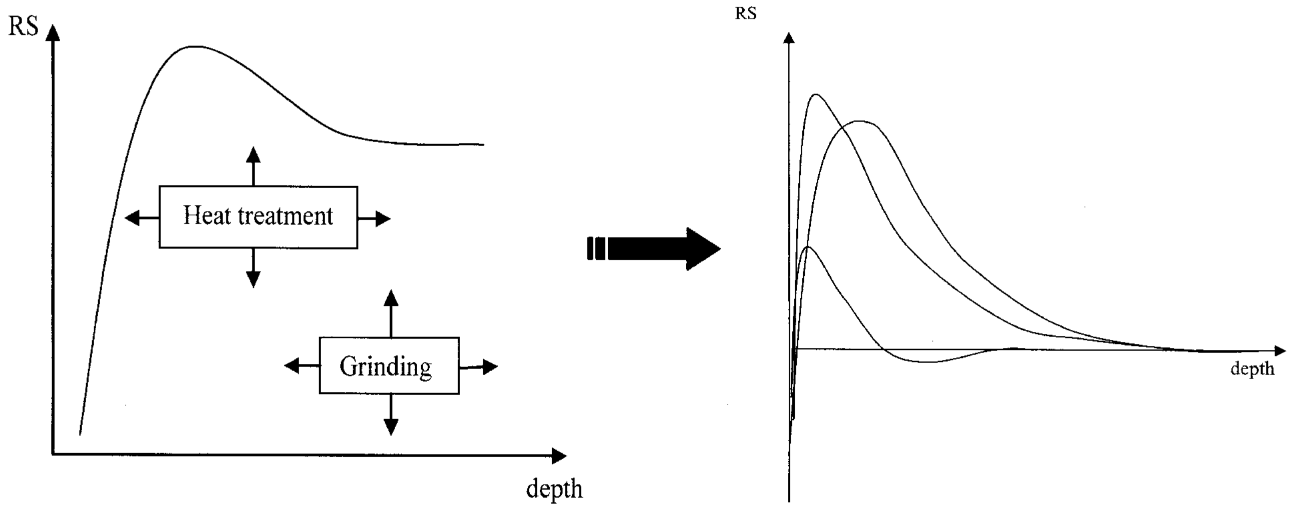

Fig. 1 RS profiles after grinding: hypothetical superposition effect of the preceding treatments on the RS distribution

fectively manipulated by using controllable tools (e.g., heat treatment or grinding); accordingly, die manufacturing procedures and parameters may be adjusted to produce the desired microstructure and surface integrity properties that would minimize the occurrence of fatigue failures.

Figure 1 schematically shows the hypothetical superposition effect of the heat treatment and grinding on the RS distribution (left-hand side) and typical RS profiles after grinding (right-hand side) (Ref 4).

Due to the temperature gradient generated in the workpiece during grinding, thermal expansion of the surface is constrained by cooler interior layers, resulting in the generation of surface compressive RS. Because the material is in an equilibrium state, high compressive RS at the surface will be balanced by subsurface tensile RS. The peak tensile stress of such RS pattern is displaced to some depth below the surface and represents "the weakest point" of the material (defined by Prevey and Field (Ref 5) as the point where the fatigue fracture initiates). As the energy and heat generated in grinding dissipate with depth propagation, some interior layers of the material will remain unaffected by grinding, and therefore corresponding RS will asymptotically approach the unstressed condition (zero level) at some depth below the surface.

Considerable work has been done in investigating the effect of the heat treatment of high-carbon, high-chromium steels (Ref 6, 7), and of grinding processes in general (Ref 4), on the properties of the material. On the other hand, very little information is available on the comprehensive analysis of performing multiple grinding passes to obtain a desired depth of cut in surface-finishing operations. Although the overall depth of the cutting passes in multipass grinding operations equals that of traditional single-pass grinding, a full spectrum of the characteristics of the material may be attained. Once a complete set of knowledge of the effect of grinding parameters and techniques is available, an engineer should fulfill the following requirements: (a) predict the nature of the RS along with their magnitude and in-depth distribution and (b) optimize cutting conditions to produce the most advantageous surface integrity characteristics and RS profile.

1.3 Research Scope

Currently, there is an information gap between the stated industrial requirements and the available theoretical knowledge. Agha and Liu (Ref 8) made the initial attempt to investigate the relationship between the initial and final RS after a number of identical cuts in face turning of AISI 52100 hardened steel. The authors found that the RS generated by the first and the second cuts significantly differed due to dissimilarity in the preexisting RS. The study was further developed by Liu and Yang (Ref 9) in a study in which the effect of multipass grinding on surface RS was evaluated. Although the authors inferred that final RS were strongly influenced by the initial RS, and that their superposition was highly nonlinear, neither examination of this effect at the subsurface level of the RS distribution nor modeling followed. Nevertheless, Prevey (Ref 10) reported that surface RS alone may be nearly independent of the grinding parameters, and knowledge of the RS distribution at the subsurface level is required to adequately complement the multipass grinding characterization. Therefore, it is imperative to know the subsurface RS distribution to infer the relationship of the processing of experimental conditions and the ultimate properties of the material. The significance and lack of knowledge on this issue motivated the design and conduct of a set of experimental treatment procedures to:

- Investigate the effect of heat treatment, grinding operations, and multipass grinding technique on the surface finish and near-surface characteristics
- Examine subsurface RS magnitude, their distribution, and tensile peak location due to main and interaction effects of the experimental factors
- Study the superposition relationship and memory aspects in the RS distributions due to the multipass grinding technique

Overall, this study introduces a new perspective on multipass grinding, focusing on estimating the effects of various combinations of the treatments involved in thread-rolling die

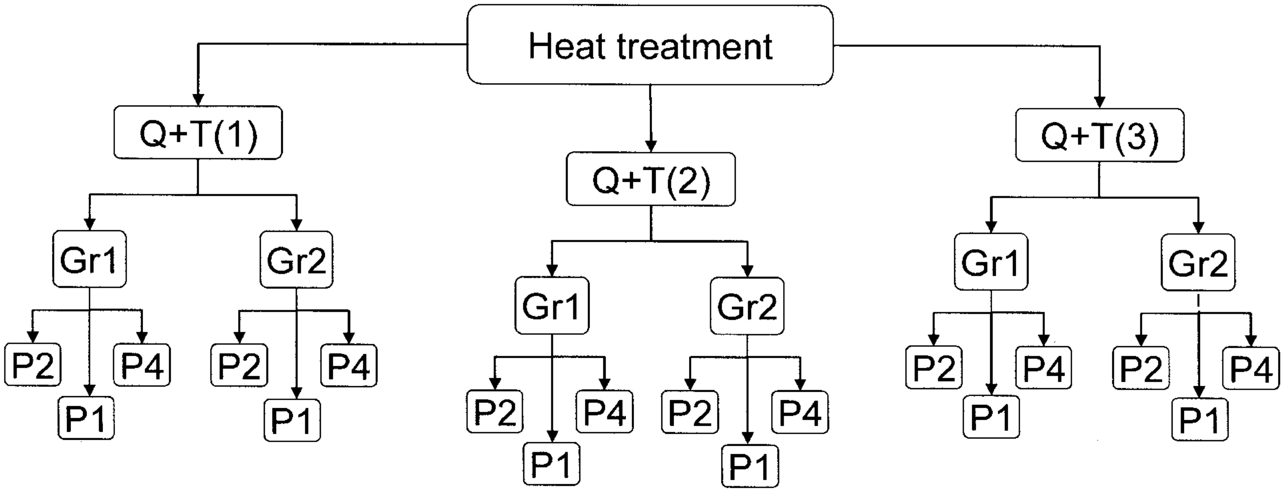

Fig. 2 Experimental model. Notation: Q + T(*i*), quenching followed by *i* cycles of tempering, $i = 1, 2, 3$ (Table 2); Gr*j*, grinding operation with *j* set of parameters, $j = 1, 2$ (Table 3); P*k*, number of passes in grinding, $k = 1, 2, 4$

preparation, on the surface integrity factor, and characteristic RS distributions. Based on the results of the study, grinding techniques for the finishing operation of the dies are reevaluated, and the most advantageous treatment combinations are suggested from current industrial practices.

2. Experimental Material and Procedures

2.1 Material and Treatment Selection

The material selected for this study was high-carbon, high-chromium D2 tool steel. Excellent hardness and resistance to wear and distortion make this steel suitable for such critical applications as long production lines in thread rolling. However, due to the exceptional strength characteristics that D2 steel exhibits toughness is sacrificed, obtaining a rating of 2 (Ref 11). At work temperatures not exceeding 205 to 260 °C, thread rolling imposes severe deformation forces and stresses from rolling, bending, and sliding. As a result, dies usually fail by spalling and crumbling before the completion of their service cycle. According to Gregory et al. (Ref 12), there is no remedy to remove and replace the dies before they have produced bad threads, because they will begin to break down long before this. Therefore, such failures can be not only interruptive to production, but sometimes catastrophic.

To ensure an appropriate combination of strength and toughness characteristics along with enhanced surface finish, the die preparation cycle generally involves heat treatment followed (or preceded) by surface finishing by grinding (Ref 3). Satisfactory toughness must be attained within the work hardness of 59 to 62 HRC to enable D2 dies to withstand cyclic deformation forces. When maximal dimensional stability and low retained austenite are required, the steels of high-alloy tool grades are double-tempered or even triple-tempered. The metallurgical basis for multiple tempering of high-alloy steels has been discussed by Roberts et al. (Ref 13). These authors argued that until the retained austenite has been completely decomposed, each cooling cycle from the tempering temperature involves the formation of secondary martensite that should be tempered again for maximal properties. In practice, D2 die heat treatment most commonly includes double tempering, while single tempering is used when greater hardness is required. The experimental design of this work included all three heat-treatment procedures (i.e., quenching followed by single-tempering, double-tempering, and triple-tempering) to allow investigation of the effect of the initial RS generated in the die by heat treatment on the final RS embedded in grinding, and to perform a comparative analysis to study the nonlinearity of the RS superposition.

2.2 Experimental Hypotheses

In thread rolling, the serration or threads on the dies should have a polished surface, while the spindle of the rolls should be as free from friction as possible (Ref 12). When lower average distortion is required, D2 dies should be ground after heat treatment. However, grinding parameters must be restricted to "nonabusive" due to the susceptibility of D2 steel to grind cracking (Ref 3). In grinding, thermal expansion and contraction are the most significant factors responsible for tensile RS generation (Ref 14); hence, to induce beneficial compressive RS, thermally induced stresses must be kept below the material's yield stress. Two sets of the grinding parameters were used in this work to comply with the consideration of the required process and the desired ultimate properties. In particular, grinding operations to the same depth were performed in one-pass, two-pass, and four-pass schemes to investigate the RS superposition and memory relationship between the stresses induced by each grinding pass. No stress-alleviation procedure was performed between the grinding passes to keep the induced stresses from the previous passes intact. Furthermore, because cutting depths of the same type as that of the multipass technique across different grinding operations were similar but not identical, a nested factorial design was applied. The factors of the study are given schematically in Fig. 2.

Theoretically several factors of the experimental design may have an affect on the RS profile. Therefore, the factors of

Table 1 D2 steel composition: sample material

Chemical composition, wt.%						
C	Cr	Mo	Si	Mn	Ni	V
1.55	11.5	0.8	0.45	0.35	0.2	0.9

interest were subdivided into several groups and assessed by the following hypotheses:

1. Overall effect of the experimental treatments:

H_0: None of the operations involved in the dies preparation would be significant.
H_1: At least one of the treatment operations would be significant.

2. Tempering effect on the RS distribution:

$$\begin{cases} H_0: \mu_{1jk} = \mu_{2jk} = \mu_{3jk}; \\ H_1: \mu_{1jk} \neq \mu_{2jk} \neq \mu_{3jk}. \end{cases} \quad \begin{cases} j - \text{grinding conditions}, j = 1, 2; \\ k - \text{multipass technique}, k = 1, 2, 3. \end{cases}$$

3. Effect of the grinding parameters on the final RS:

$$\begin{cases} H_0: \mu_{i1k} = \mu_{i2k}; \\ H_1: \mu_{i1k} \neq \mu_{i2k}. \end{cases} \quad \begin{cases} i - \text{tempering cycles}, i = 1, 2, 3 \\ k - \text{multipass technique}, k = 1, 2, 3. \end{cases}$$

4. Heat-treatment and grinding interaction effects:

$$\begin{cases} H_0: \mu_{11k} = \mu_{12k} = \mu_{21k} = \mu_{22k} = \mu_{31k} = \mu_{32k}; \\ H_1: \mu_{11k} \neq \mu_{12k} \neq \mu_{21k} \neq \mu_{22k} \neq \mu_{31k} \neq \mu_{32k}. \end{cases}$$
$$k - \text{multipass technique}, k = 1, 2, 3.$$

5. Multipass grinding effect on the RS superposition:

$$\begin{cases} H_0: \mu_{ij1} = \mu_{ij2} = \mu_{ij3}; \\ H_1: \mu_{ij1} \neq \mu_{ij2} \neq \mu_{ij3}. \end{cases} \quad \begin{cases} i - \text{tempering cycles}, i = 1, 2, 3; \\ j - \text{grinding conditions}, j = 1, 2. \end{cases}$$

The above hypotheses were evaluated by the analysis of variance, where the F-test was set at a 0.05 level of significance. Variances observed in the RS would first be partitioned into main effects, their interactions, and pure randomness. Then, if found significant, the variances will be compared among the levels of each factor to identify the optimal performance and trade-off for deviation from the optimum.

Three types of validity were applicable in this work: (a) internal validity, assured by using a significant statistical relationship between dependent and independent variables, (b) construct validity, which reproduced the experimental setting of most commonly used and representable industrial operations for the given application, and (c) external validity, which was achieved through experiment repeatability.

2.3 Experimental Protocol

The chemical content of the D2 high-carbon, high-chromium steel used in the study is given in Table 1. Thirty-six specimens were prepared by cutting from adjacent sections of the same bar to a final configuration of 2.54 cm length, 1.25 cm width, and 1.25 cm thickness. The specimens were then randomly distributed among the three heat-treatment groups detailed in Table 2. Microstructural analysis, hardness-toughness testing, and surface RS examination were accomplished at this step. Subsequently, the preparation of the specimens was completed by various grinding operations of the different multipass techniques. Grinding procedures (Table 3) were performed using an automatic reciprocating surface grinder with a 220-grit, diamond-bonded wheel, 15.25 cm in diameter. Achievement of the uniform material removal rate parallelism of the grinding wheel to the specimen was assured by making an initial "cleaning" cut of one side of the specimens prior to the grinding operation of interest.

RS measurements were collected via x-ray diffraction (XRD) coupled with electrolytic polishing, and the settings of the electropolisher were set to remove a layer ~25.4 μm from the surface at a time. RS were collected at each depth step until negligible values were reached. The characteristics of the XRD equipment and detailed information on the experimental conditions are given in Table 4. The multiple exposure technique allowed measurements of the RS at various angles to the diffracting planes, and helped to eliminate the nonlinearity of d versus $\sin^2 \psi$ due to significant amounts of plastic deformation caused by machining operations (Ref 15).

The amount of the retained austenite was quantified as the ratio of the integrated intensity curves obtained from the 2θ angles at 128° and 156°, corresponding to the (211) and (220) diffracting planes of the body-centered tetragonal (bct) and face-centered cubic (fcc) crystal structures of martensite and austenite, respectively. The position of the K_α diffraction peak, intensity, and peak breadth were determined by Pearson VII distribution:

$$Y(2\Theta) = \frac{I_0\sqrt{C}}{\pi H_k}\left[\frac{1}{1 + C\left(\frac{2\Theta_i - 2\Theta_k}{H_k}\right)^2}\right]^m$$

$$\begin{cases} C = 4(2^{1/m} - 1) \\ H_k = \sqrt{U \cdot tg^2\Theta_k + V \cdot tg\Theta_k + W + P/\cos^2 \Theta_k} \end{cases}$$

where U, V, W, P, and m are arbitrary parameters, and were fitted using SAS Proc NLIN procedure (SAS Institute, Cary, NC). Calibration procedures of the collected XRD data included correction for background intensity, absorption, and Lorentz polarization.

3. Results and Analysis

Due to the interdependent nature of the experimental treatments, it is expected that some characteristics induced during heat treatment will be carried over to the properties of the final part upon grinding. To correctly evaluate the experimental data and to distinguish the effect of each experimental factor alone and their possible interactions, the scheme of the experimental observations first included analysis of the heat-treatment effect, followed by the grinding effect on the surface integrity factor and the RS distribution in the final part.

Table 2 Heat treatment procedures of D2 specimens

	Preheat	Hardening	Tempering		
			Cycle 1	Cycle 2	Cycle 3
Q + T(1)	815 °C, 12 min	1010 °C, 40 min	205 °C, 2 h	…	…
Q + T(2)	815 °C, 12 min	1010 °C, 40 min	515 °C, 2 h	480 °C, 2 h	…
Q + T(3)	815 °C, 12 min	1010 °C, 40 min	540 °C, 2 h	515 °C, 2 h	495 °C, 2 h

Table 3 Grinding parameters of surface finishing

Parameters	Grinding condition 1	Grinding condition 2
Wheel speed	1651 m/min	1651 m/min
Spindle speed	3450 rpm	3450 rpm
Feed rate	1.02 m/min	1.02 m/min
Total depth of cut	25.4 μm	12.7 μm
Number of passes	1, 2, 4	1, 2, 4
Coolant	CIMSTAR 3865	CIMSTAR 3865

Table 4 X-ray diffraction equipment characteristics

Radiation	$Cr\text{-}K_\alpha$
Reflection: lattice plane, Braggis angle	BCT (211), 156°
Specimen orientation angles, ψ	−11.95°, 0°, 11.95°
Irradiated area	1 mm^2
Tube voltage	17 kV
Tube current	20 mA

3.1 Microstructural Analysis

Figure 3 shows the results of the microstructural examination of D2 steel in the (a) as-quenched condition, (b) single-tempered condition, (c) double-tempered condition, and (d) triple-tempered condition. Specimens were characterized upon quenching by a structure composed of martensite, undissolved carbides, and retained austenite that were produced upon cooling from the austenizing temperatures. Untempered martensite is highly unstable due to high dislocation density, and the supersaturation of carbon and alloy atoms in the bct crystal lattice of the martensite (Ref 11). Therefore, hardened tool steels are always tempered, which increases the toughness and stability of the structural components. Based on Fig. 3, the primary microstructural changes in the differently tempered components were observed in the shape, amount, and distribution of the carbide particles in the martensitic matrix.

Microstructures of multiple-tempered specimens were defined by higher uniformity of the size of the carbides and their distribution, while small and large coarse carbide particles coexisted with each other in the microstructures upon single tempering. Along with the transformation of the martensite morphology, tempering causes decomposition of the retained austenite, which introduced additional carbides at various tempering stages. Accordingly, the microstructures obtained on double-tempered and triple-tempered specimens revealed larger volume fractions of the carbide particles per unit area when compared with those of single-tempered practice. The increasing quantities of uniformly distributed alloy carbides in the martensitic matrix of D2 steel are beneficial because they control the austenite grain boundaries contributing to a greater wear resistance.

3.2 Hardness-Toughness Examination

The results of the hardness examination along with corresponding impact testing data are shown in Fig. 4. A hardness decrease was associated with the number of tempering cycles and was caused by the effect of greater tempering temperatures and holding time (Table 2) on microstructural transformations. A secondary hardening effect was observed on triple-tempered specimens that correlated to the formation of fine alloy carbides observed in microstructural examination (Fig. 3d) and was explained by the following two phenomena:

- More carbon and alloy elements are taken into solution in multiple tempering at 480 to 540 °C and, therefore, are available for carbide precipitation
- A large portion of the retained austenite undergoes "conditioning" in the range of tempering temperatures mentioned previously, which triggers large quantities of secondary martensite to be formed on cooling from the reheating temperature (Ref 16)

In medium- to high-alloy steels, this precipitation of alloy carbides, together with the conditioning and transformation of highly alloyed retained austenite, is believed to be responsible for the secondary hardening effect (Ref 13). As a result, a set of carbide-forming alloying elements in D2 (i.e., chromium (Cr), molybdenum (Mo), and vanadium (V)) sufficed to resist softening at high tempering temperatures and, along with the retained austenite transformation, augmented the effect of secondary hardening. However, in practical use secondary hardening is rarely used due to "increased movements and greater possibility of breakage" (Ref 13).

Being inversely dependent, the impact strength of the specimens was shown to grow proportionally as hardness decreased. Compared with double-tempered specimens, single-tempered specimens exhibited lower impact strength. The latter was explained by the microstructure consisting of high-carbon martensite and a high density of coarse undissolved carbides, which served as fracture-initiation sites (Ref 11). As expected, additional high-temperature tempering cycles improved toughness; however, its value dropped in triple-tempered specimens. According to Bain and Paxton (Ref 16), such temper embrittlement is characteristic of chromium steels when tempered in the range of 480 to 540 °C with additional subsequent tempering cycles at temperatures near but below A_{c_1} temperature.

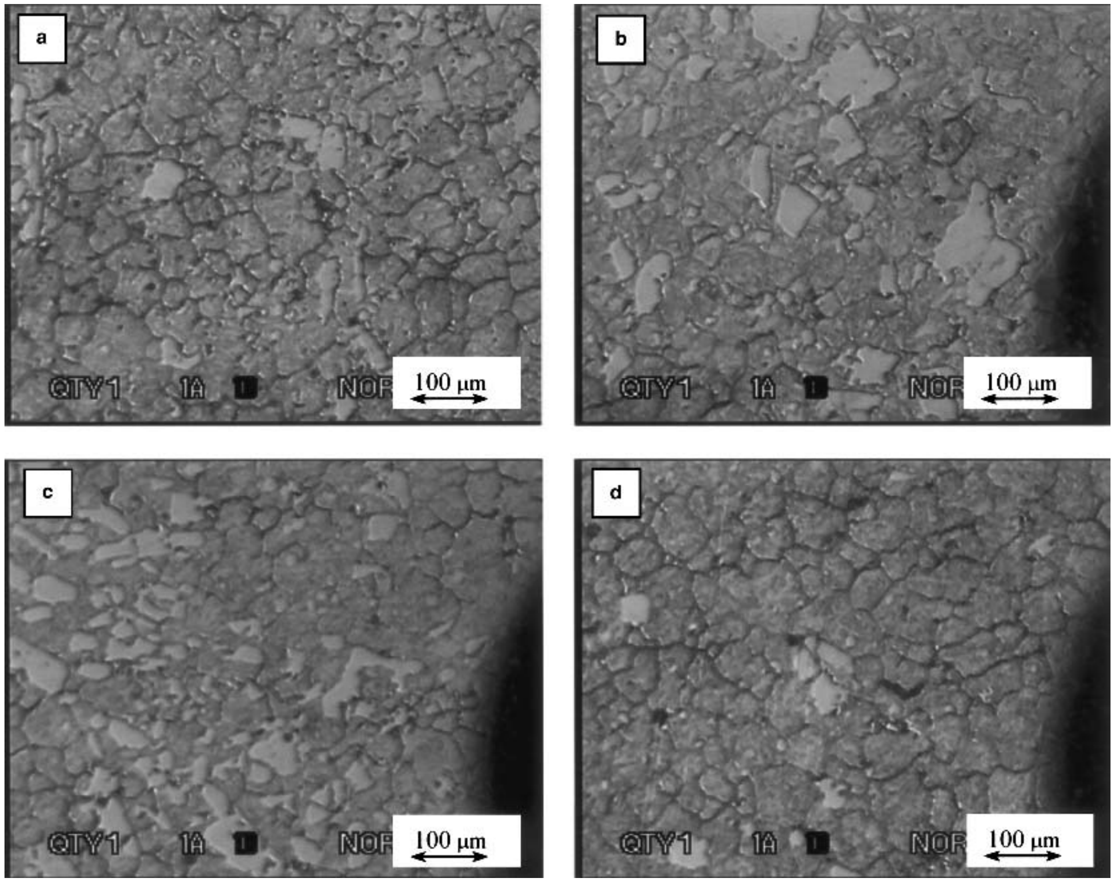

Fig. 3 Microstructures of D2 steel in (a) as-quenched condition, (b) single-tempered condition, (c) double-tempered condition, and (d) triple-tempered condition. The particles shown in white, carbides embedded in martensitic matrix; retained austenite is present along the martensite grain boundaries. Specimens were air-quenched from 1010 °C, 2% nital etch; magnification, 100×

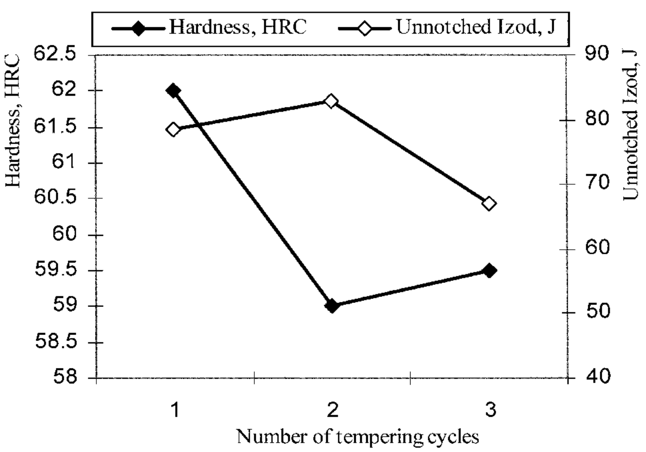

Fig. 4 Hardness and unnotched Izod strength values

3.3 Roughness Examination

The results of the roughness examination of the ground specimens in both longitudinal and transverse directions are given in Table 5. Surface roughness in the longitudinal direction was found to be significantly dependent on the type of grinding operation. Forces generated in grinding to a smaller depth tend to remove material more evenly and uniformly, producing a better surface finish. Multipass grinding caused slight roughness variations; however, the effect itself was not significant at a $\alpha = 0.05$ significance level. Surface roughness examination in the transverse direction revealed no significant effect with respect either to the type of grinding operation or the grinding technique.

Table 5 Roughness examination (µm)

	Longitudinal direction		Transverse direction	
Grinding technique	**Grinding operation 1**	**Grinding operation 2**	**Grinding operation 1**	**Grinding operation 2**
1 pass	0.381 ± 0.040	0.259 ± 0.021	0.747 ± 0.073	0.732 ± 0.021
2 passes	0.351 ± 0.028	0.254 ± 0.040	0.777 ± 0.023	0.777 ± 0.029
4 passes	0.366 ± 0.029	0.274 ± 0.042	0.737 ± 0.031	0.737 ± 0.040

3.4 Surface RS and Retained Austenite

It is accepted (Ref 8) that the final RSs are strongly influenced by the initial RS. For this reason, RS generation related to grinding was distinguished by analyzing specimens within each individual heat-treatment group. Furthermore, to account for the effect of both treatment operations (heat treatment and grinding) and their possible interactions, the final RS profiles were assessed by the hypotheses listed previously.

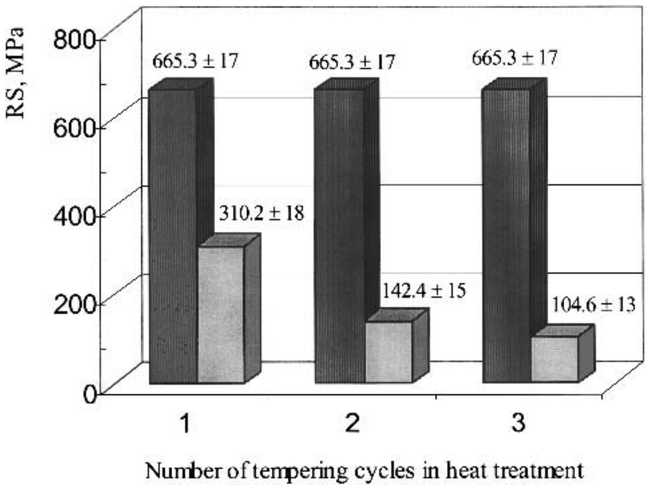

Fig. 5 Surface residual stresses on D2 steel samples after heat-treatment practice: black, as-quenched condition; gray, quenched and tempered specimens

The results of the surface RS observed on the specimens prior to grinding are depicted in Fig. 5. Two characteristics can be inferred from this figure: (a) RS contrast across specimens of different heat-treatment groups and (b) the degree of the RS relaxation due to the number of tempering cycles. Initially, high-tensile RS were generated in the surface of the hardened specimens due to rapid thermal contraction of the outer layers of the material in air cooling from 1010 °C. The RS in such a condition are highly unstable and make the material susceptible to cracks and other failure-related defects. Therefore, tempering is performed to cause structural changes, as revealed in Fig. 3, and to reduce the magnitude of these stresses.

Every tempering practice used in the study contributed to stabilizing the structure by converting unstable brittle martensite into tempered martensite and transforming retained austenite into martensite (Table 6). Accordingly, RS of the tempered components were significantly lowered toward more compressive values compared with those of the as-quenched condition. The more tempering cycles are involved, the lower the tensile stresses observed. Although every tempering practice contributed to the relaxation of RS, the effect of the multiple tempering was found to be nonlinear. In essence, the most significant amount of RS relaxation occurred during single tempering, and even though tempering operations that involved additional tempering cycles relieved more internal stresses, the increment of the stress relaxation per each cycle was marginal.

To gain a better understanding of the main driving forces in the RS generation it is important to estimate the relative volume fraction of the decomposed phases. As such, the amount of surface retained austenite in the specimens before and after grinding was measured and recorded in Table 6. It was observed that a very large proportion of the austenite did not transform in the D2 specimens. Such a significant quantity (34.8%) is explained by the effect of the alloy content on M_s temperature, which is significantly lowered by the presence of substantial amounts of carbon, Cr, and Mo in the D2 steel (Table 1). When comparing the amounts of the austenite retained in the structures of differently heat-treated groups, the effect of time and tempering temperatures must be considered. Due to the great stability of the retained austenite in D2 steel, its decomposition becomes possible only in the range of 480 to 540 °C (Ref 13); accordingly, the maximum retained austenite transformed was observed in the triple-tempered specimens as opposed to the single-tempered ones.

Table 6 Surface retained austenite measurements (%) of all treatment conditions

Heat treatment	Non-ground	Grinding condition 1			Grinding condition 2		
		1-pass	2-pass	4-pass	1-pass	2-pass	4-pass
Q + T(1)	32.9	25.8	16.4	14.1	20.5	13.8	10.6
Q + T(2)	6.1	4.8	3.9	3.3	3.4	2.7	2.3
Q + T(3)	3.3	2.7	2.4	1.8	2.5	1.9	1.6
As-quenched	34.8						

Analysis of the retained austenite of the final parts revealed that both grinding factors (i.e., the process conditions and multipass grinding technique) further advanced decomposition of the retained austenite into martensite. The magnitude of this phase transformation was strongly influenced by the amount of the austenite remaining untransformed in the specimens upon heat treatment (Table 6). According to El-Helieby and Rowe (Ref 17), structural changes in the material due to grinding should be treated as a function of temperature and time in the grinding wheel-workpiece contact. Based on the experimental setup of this study, it appears that the cutting depth and number of passes were primary factors that characterized the temperature generated at the surface of the workpiece during grinding and the time taken to perform the operation, respectively. The time effect was proportional to the number of passes involved in grinding, and its increase in multipass operations also contributed to the retained austenite transformation.

3.5 Sources of RS Variability

Prior to analyzing the effect of the proposed hypotheses on the RS distributions, the partitioning of sum of squares (SS) for each experimental model was delineated in the form of pie charts (Fig. 6) to investigate the sources of RS variability. Figure 6(a) shows that the SS of the variance can be explained by different effects and their interactions. It is clear that the depth effect of the RS distribution consumes almost three quarters of the variation, and the second largest explanatory factor is the multipass techniques nested in the grinding conditions. In addition, all factors of interest revealed significant effect; therefore, they were further considered individually (Fig. 6b-e).

The sources of randomness, or scatter, of the RS (defined as pure error terms with normality tested using *Q-Q* plots at a 0.05 level of significance) were used to show the amount of variation that explains the hypothetical effects of the experimental factors compared with that of pure error. When evaluating interaction effects of the heat treatment and grinding, it appears that the major source of variation of the final RS profile comes from the tempering effect. Grinding was also significantly notable; however, it was predetermined by the state of the RS induced from the heat treatment. As shown in Fig.

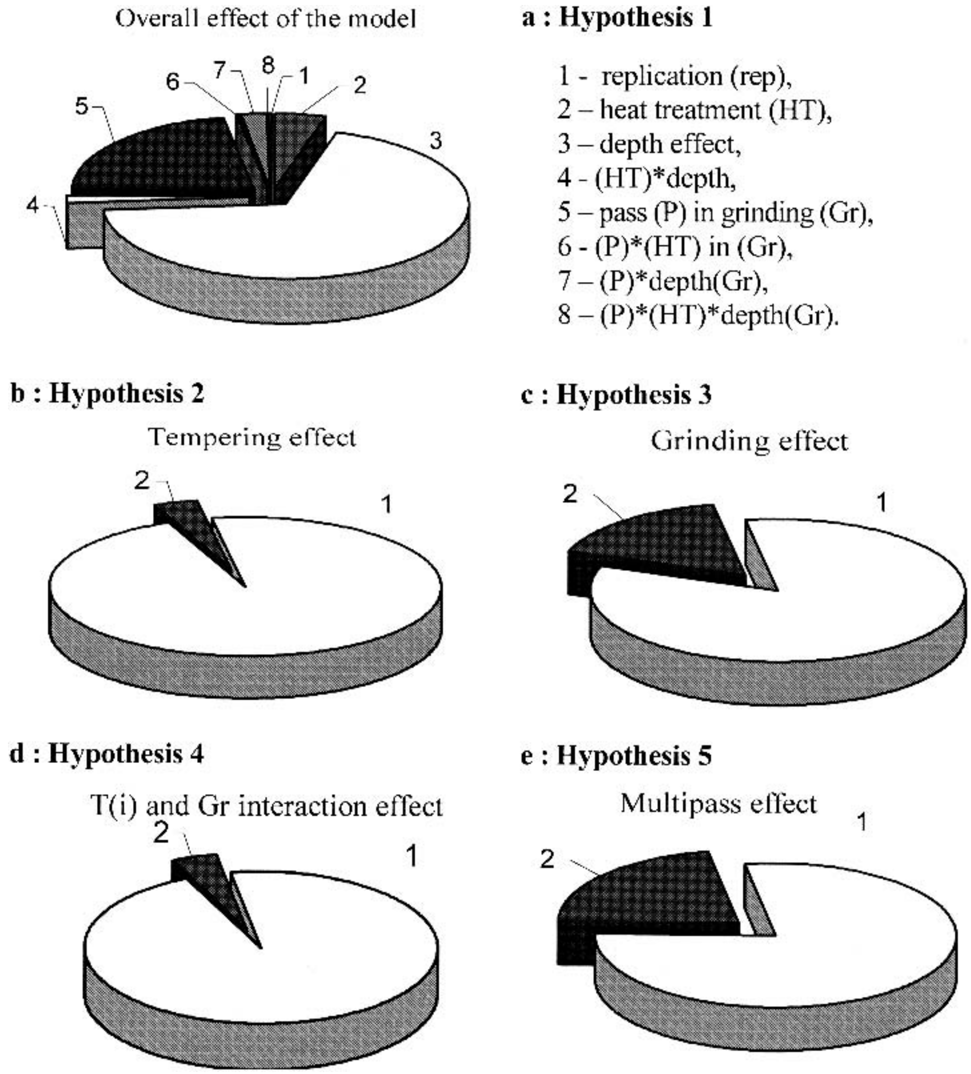

Fig. 6 SS partitions of the experimental model by hypotheses: 1, effect of interest (by each hypothesis); 2, pure error term

6(e) and (c), substantial variation in the RS was caused by the multipass grinding, yet its effect was embedded in that of the grinding conditions.

3.6 Subsurface RS Profiles

To facilitate the discussion of the nature and the origin of the RS due to the major explanatory factors defined in Fig. 6 (i.e., the depth of the RS distribution), Fig. 7 shows subsurface RS distributions for all possible combinations of the experimental factors. As before, the analysis of the RS profiles was carried out to ensure identical preexisting RS and to reach an unbiased estimation of their superposition.

The tempering effect on the RS distribution revealed a similar trend across all grinding operations: single-tempered specimens exhibited lower surface compressive RS and greater subsurface tensile stresses as opposed to those of multiple-tempered specimens. Because the transformation of the retained austenite into martensite that was reported in Table 6 was associated with the volume increase of the specimens, the retained austenite decomposition is believed to contribute to the generation of compressive RS (Ref 18). Accordingly, the largest degree of retained austenite decomposition occurred during the triple-tempering process, which advanced the structure stabilization of the material and consequently promoted greater compressive and lower tensile RS of the final parts.

As expected, grinding successfully reversed tensile surface RS into compressive ones in all tempered specimens. Such stress transformation was triggered by the temperature gradient generated in the specimens. In particular, the rise of the workpiece temperature in grinding causes expansion of the near-surface layers of the material. On the other hand, energy entering the specimens dissipates with depth propagation and leaves interior layers of the material considerably cooler compared with those at the surface level. As a result of the competing processes of thermal expansion and interior contraction, surface compressive RS form. Given that the summation of the net forces in an equilibrium state is equal to zero, the compressive RS generated in the surface are balanced by the tensile subsurface ones.

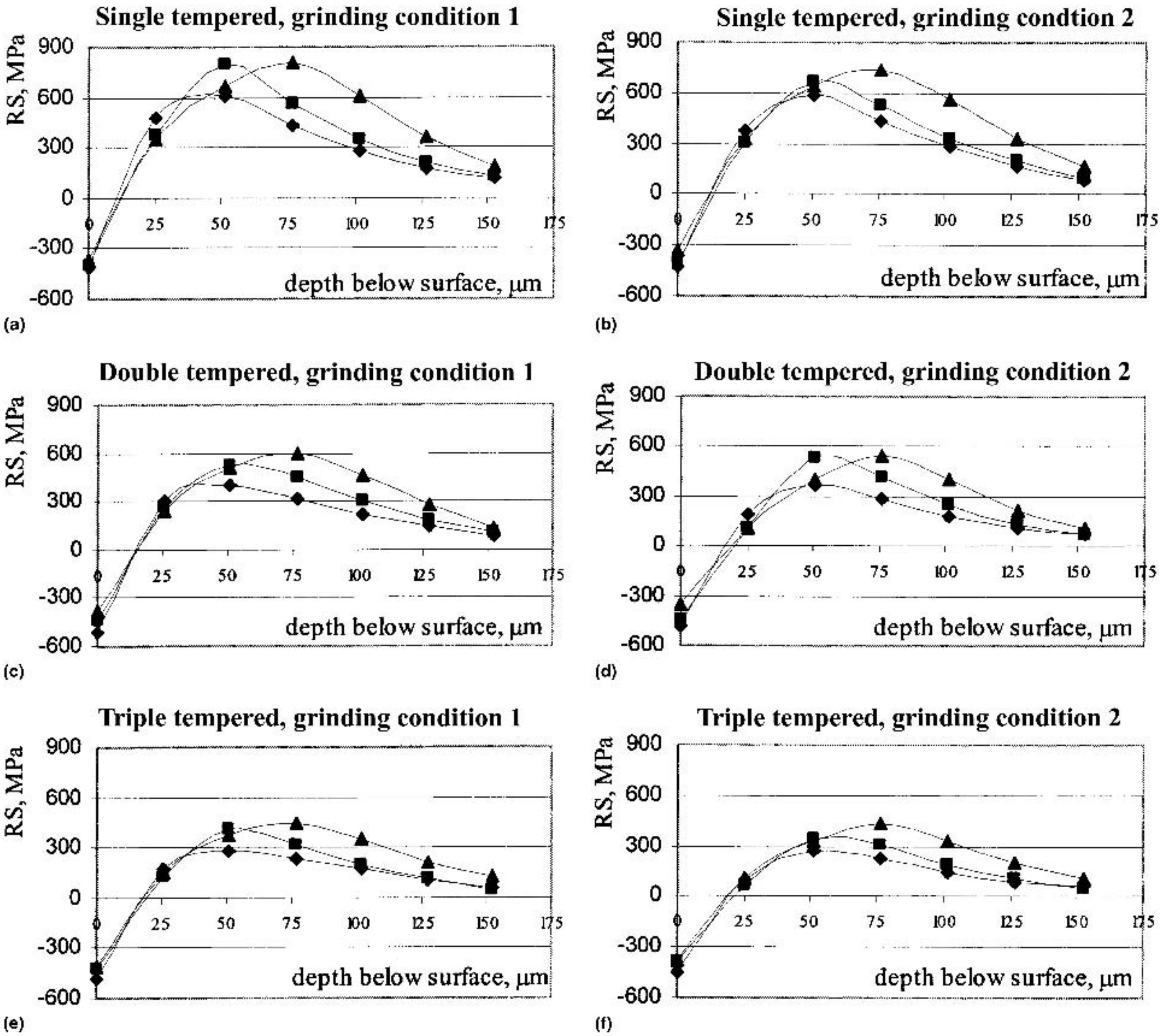

Fig. 7 Residual stress distribution: (a, c, e) after finishing by grinding operation 1 on single-, double-, and triple-tempered D2 samples, respectively; (b, d, f) after finishing by grinding operation 2 on single-tempered, double-tempered, and triple-tempered D2 steel samples, respectively. Notation: ▲, one-pass grinding technique; ■, two-pass grinding technique; and ◆, four-pass grinding technique

The effect produced by the grinding conditions on the distribution of subsurface RS was found to be significant at each depth except for the surface RS. Thus, in the given experimental settings, it was inferred that surface RS were independent of the grinding conditions, which conformed to the findings by Prevey (Ref 10) and emphasized the need for subsurface RS investigation. Grinding operation of condition 1, in which the depth of cut was experimentally set to be twice as large as that of the alternative operation, produced greater deformation forces acting on the workpiece. As a result, specimens ground by the set of grinding condition 1 exhibited greater subsurface tensile RS and, therefore, a larger amplitude of the stresses from surface to subsurface layers within the affected depth of the specimens.

Along with a vertical shift of the RS profile, which is characteristic for the effects of heat treatment and grinding conditions, multipass grinding introduced a displacement of the tensile peak toward the surface. From Fig. 6, it appears that regardless of the treatment of the preceding material, RS profiles of all specimens, in which preparation differed by only the number of grinding passes, exhibited a similar trend. The latter observation suggests that a superposition relationship, or an "orthogonal" memory between the passes of the same grinding operation, exists.

Because the total cutting depth of multipass operations within the same type of grinding conditions was equal to that of a single-pass operation, the forces applied in grinding were proportional to the cutting depth increase/decrease. Accordingly, the temperatures generated at the surface of the workpiece during multipass grinding, and consequently, the amount of heat entering the workpiece, were significantly lower than those of single-pass technique. As a result, smaller plastic de-

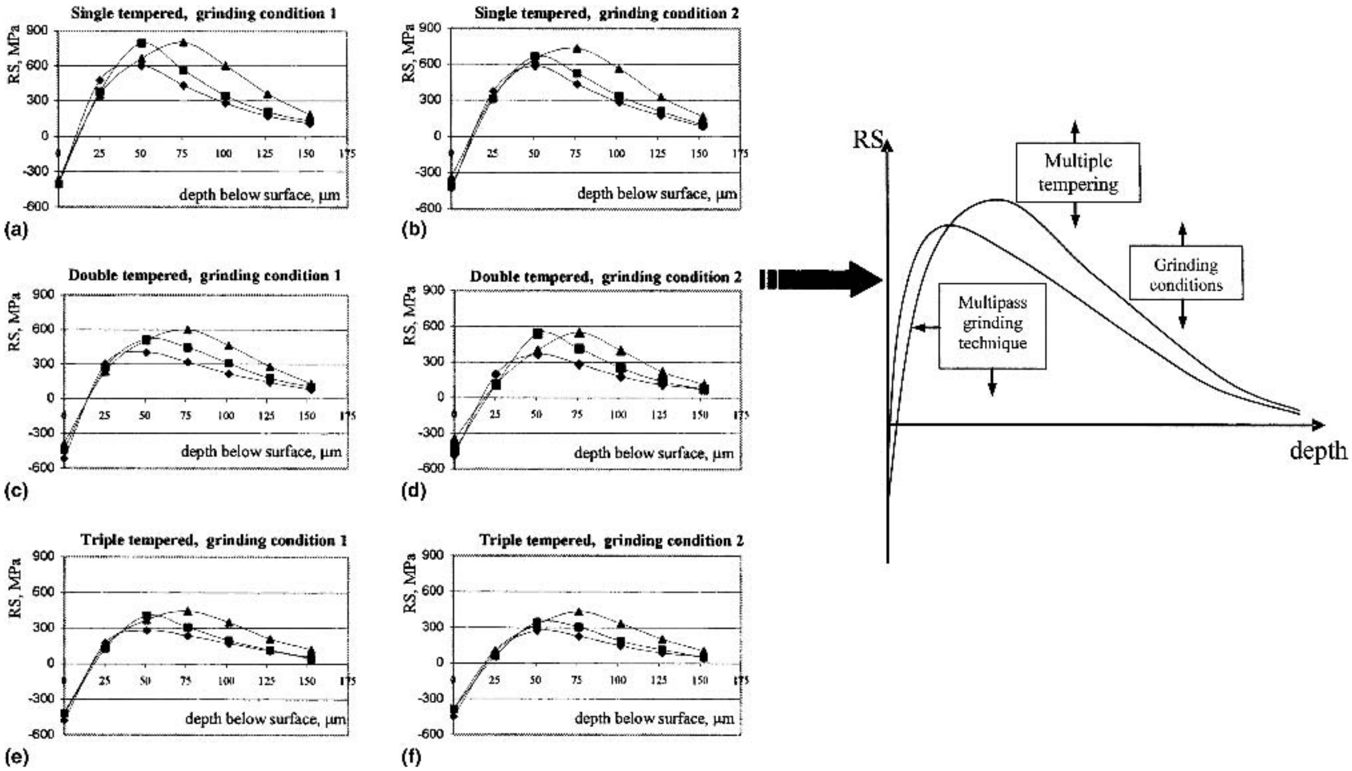

Fig. 8 Final RS profiles and the derived effect based on the experimental findings

formation forces were generated, which decreased the magnitude of the RS and the depth of the affected layers causing the tensile peak to shift toward the surface layers. Locating the tensile peak is of industrial significance because its characteristics are correlated to the fatigue life of the final part. In particular, the depth at which the tensile peak occurs is generally accepted to be the point where fatigue fracture starts (Ref 4), while the magnitude of the peak defines the number of cycles that the part can withstand before fracture initiates. Even though the tensile peak in this study was observed to shift toward the surface layers of the workpiece, its fatigue life-diminishing characteristics would be counteracted by the lower tensile RS. Therefore, it is certain that the overall resultant RS patterns would contribute to the longer service life of thread-rolling dies.

Overall, it was observed that when a factor improves the RS, surface integrity performance tends to move in the positive direction. In essence, beneficial RS distributions (defined by greater surface compressive RS and lower subsurface tensile RS) were observed on the specimens of higher surface integrity, and vice versa. The individual effect of the three experimental factors on the dynamics of the RS generation and their in-depth distribution is schematically depicted in Fig. 8. Heat-treatment and grinding conditions caused a vertical shift of the RS pattern. The introduction of additional tempering cycles and the use of less severe grinding conditions significantly reduced the tensile peak magnitude, causing a smaller degree of RS alteration with depth propagation. Multipass grinding both lowered the tensile subsurface RS and caused the tensile peak shift toward the surface layers.

RS is an unavoidable by-product of the manufacturing processes involved in the preparation of a part. As hypothesized in Section 2.2, the RS can be controlled and unique patterns may be derived by applying the optimal values of parameters in the manufacturing processes. Because the distribution of the RS is not linearly dependent on the heat treatment and multipass grinding, a nested experimental design is needed. To summarize the result, the effects of all the factors and their interactions were compared, and multiple comparisons were performed based on the statistical significance of the effect. The significant interactions of the experimental factors indicate that the optimal setting of the factors may need to be controlled concomitantly to avoid a suboptimal result and to benefit from improved RS profiles.

4. Conclusions

With the goal of understanding the nature of RS and surface integrity, the thesis of this study was that the analysis of variability in RS provides a powerful tool in pointing to their underlying functional and structural development. The mathematical description of this variability is a potentially important aspect of the modeling of the RS because it indicates the optimal treatment and sensitivity of such an approach. To summarize the observation, the major findings are:

- Microstructural transformations due to heat treatment were revealed mainly in the shape and distribution of the carbide phase in the martensitic matrix, as well as retained austenite transformation. Upon single-tempering, approximately 5% of the austenite phase transformed (compared with as-quenched condition), whereas 82 and 90% austenite, respectively, decomposed during high-temperature double-tempering and triple-tempering cycles.

- Secondary hardening on triple-tempered specimens resulted from the conditioning reaction of the retained austenite in the range of 480 to 540 °C and carbide precipitation. However, due to increased brittleness, the contribution of secondary hardness is not commensurable with the toughness loss. As such, the use of triple-tempering cycles in the heat treatment of D2 dies is difficult to rationalize.
- The effect of both heat treatment and grinding operations was found to be significant at all depths of the RS profiles. Analysis of the RS patterns due to these factors revealed a parallel shift, while the significance of the effect of their interactions indicated the nonlinear nature of their superposition.
- Regardless the combination of the heat treatment and grinding conditions, multipass grinding produced particular RS patterns. This observation suggests that superposition between the grinding passes is evident and should be studied further.
- Based on multiple comparisons, the double tempering of D2 dies should be completed by grinding using a smaller depth increment in the multipass technique. The proposed treatment would improve surface integrity, allowing the dies to withstand potential spalling and crumbling, and would promote beneficial RS distribution, enabling longer service life prior to failure.

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