this is not the only source of variation. Grinding is a nonhomogeneous process and certain areas may be more severely abraded than others and this could result in a nonhomogeneity of residual stress. In computing the residual stresses the moduli values were assumed to be isotropic while this is known to be not true except as a first approximation.

The interferometric method also is subject to some of the limitations listed in the foregoing and, in addition, is probably not sensitive enough to provide reliable values for stresses within the first 0.0005 in. below the surface. In addition, there are other possible sources of error such as in the measurements of the optical interference bands, variations in etching, residual stresses from heat-treatment, and so on.

While absolute limits on the accuracy of either method cannot be stated explicitly, it is believed that certainly the magnitude and sense of the stresses have been determined adequately.

Conclusions

1 All grinding stresses are relatively superficial, not exceeding 0.006 in. in depth on the average.

2 Critically high stresses and stress gradients do not exceed 0.002 to 0.003 in. in depth below the ground surfaces.

3 The greater the severity of grinding, the greater is the magnitude of the residual stress.

4 Severe grinding produces predominantly tensile surface stresses while less severe grinding can produce compressive surface stresses although in most cases severe stress gradients can exist near the surface layer for all kinds of grinding.

5 The higher the hardness level of the steel, the greater is the residual stress and residual-stress gradients that exist in the ground surface.

Acknowledgment

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Discussion

J. L. Beaton.[5] The necessity for evaluation of effects of grinding has of recent years assumed ever-larger proportions. Microstructural changes of rehardening and retempering during abusive grinding have received attention in view of their demonstrated deleterious effect on cutting-tool life. Further than this, applications involving necessity for electroplating subsequent to grinding operations, have resulted in demonstrations of high-order residual stresses in superficial layers of ground surfaces when additive stress-corrosion or hydrogen-embrittling effects of the electroplating operation or preparatory chemical cleaning have resulted in cracking of the steel beneath the plate. While metallurgical transformations of steel surfaces during grinding are probably the worst offenders in promoting high-order stresses that result in such "grinding checks," introduction of stresses by abusive grinding short of resulting in transformation may be of an order sufficient to result in the same effect. Indeed, supplemented by inherently introduced tensile stresses of certain electroplates such as chromium, tensile stresses induced in grinding may easily tip the balance toward premature fatigue failures even though cracking may not have resulted during the plating operation itself.

Because of serious economic factors in loss of material in finished stages of fabrication as well as possible structural inadequacies in service involving fatigue, it was obvious that a tool capable of evaluating grinding practices for their degree of effect on structural behavior needed to be developed. It is believed that the authors have applied techniques to the problem that have demonstrated their applicability by confirmation of theoretically derived data as well as certain effects noted in large-scale production of electroplated high-strength steel cylinders. Certainly the studies have not provided the final solution, but the authors are to be congratulated on furthering the art and demonstrating a useful technique capable of performing invaluable service in developing grinding wheels and grinding techniques that will be most suitable to critical applications.

It is hoped that this progress will be integrated into the overall progress of grinding in efficiency of metal removal and production of surface finish so that the proper balance is attained and due regard may be paid to the aspects developed in this work where residual stresses may play a significant role.

[5] Bendix Products Division, South Bend, Ind.

R. E. Ogilvie.[6] With regard to the x-ray stress-measuring technique described in the paper, the authors realize the insensitivity of the diffraction line used, but the writer questions whether they realize the exact magnitude of the errors. The stress constant is about 10,000 psi per 0.01 deg in theta. The writer is quite certain that the line position from a hardened-steel specimen cannot be determined better than 0.02 to 0.03 deg. This would mean a probable error in the measured stress of 20,000 to 30,000 psi.

The writer can see no reason why chromium radiation was not used in measuring the 211 line with the two-exposure technique. This would remove any doubt as to the effect on the interatomic spacing in the tempered and rehardened layer due to grinding. This effect has not been taken into account in this investigation. The stress constant would be about 1600 psi per 0.01 deg or an increase in sensitivity by a factor of 6.

The line position need not be the true position of the $K\alpha_1$ but any reference point may be used as long as it is consistent for the normal and oblique measurement. The peak position may be measured by fitting a parabola to the peak by the method of least squares or a technique used by Timken Roller Bearing Company where they extrapolate straight lines on the side of the peak, the intersection of these lines being the reference position. This procedure works in their case but it is believed in the higher-tempered steels investigated that this method will not work. The

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center of gravity also may be used; however, this requires that the background be reached on both sides of the peak.

Considerable refinements are necessary but this is definitely a step in the right direction, and it is hoped that further work will be done along these lines.

H. R. Letner.[7] The results which the authors have presented are indeed a welcome addition to the relatively small fund of experimental information available on the effect of conditions of grinding and workpiece material upon residual grinding stresses. It is encouraging to see objective studies, such as this one, furnish information to supplant "grinding stresses are tensile stresses" generalities in engineering literature.

Although the authors' data adequately support their conclusions for the SAE 4340 steel which they used, our own research on another steel indicates that their fifth conclusion may be limited in its generality. Fig. 11 of this discussion typifies the variation of residual grinding stress with heat-treatment which we have consistently observed in experiments with manganese oil-hardening tool steel (0.92 C, 1.38 Mn, 0.019 P, 0.28 S, 0.013 Si, 0.45 Cr, 0.41 W). These data were obtained from 2-in-square specimens austenitized at 1475 F, quenched in oil, and tempered as indicated.

At the end of the grinding test in question, the specimens were 0.198 in. thick, 0.036 in. having been removed from the test surface of each specimen following heat-treatment. The six specimens were placed in a row on the chuck of a horizontal-spindle, reciprocating-table-type surface grinder and ground dry with a $7\frac{3}{8}$-in. × $\frac{1}{2}$-in. × $1\frac{1}{4}$-in. 38A461-J8VBE wheel. The wheel speed was 6000 fpm, traverse speed 60 fpm, unit crossfeed 0.050 in., and unit downfeed 0.001 in.

The average stress decreases with decreasing hardness until it reaches a minimum in the neighborhood of RC-54 to RC-47, then increases as the hardness continues downward. The thickness of the stressed layer exhibits a similar behavior, reaching a minimum value of 0.0007 in. in the RC-47 test piece, which is about one tenth of its value in the RC-64 and RC-12 specimens. Comparison of the behavior of this steel with the authors' SAE 4340 suggests that the effect of prior heat-treatment upon residual stresses induced by grinding is different for steels of different compositions.

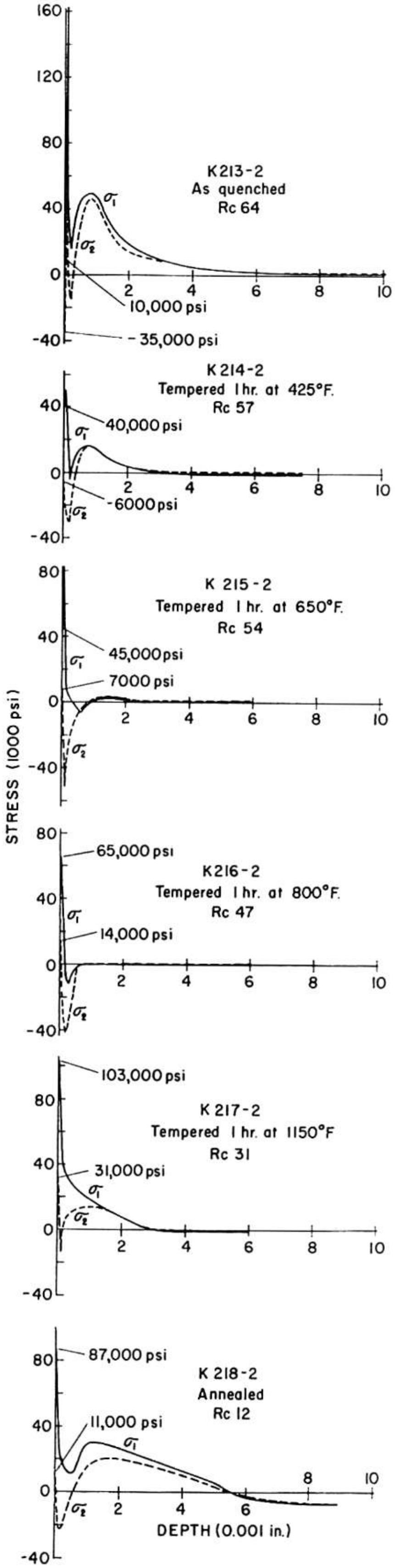

Fig. 11 Effect of Prior Heat-Treatment of Tool Steel Upon Residual Stresses Induced by Surface Grinding. Principal Stresses Parallel and Perpendicular to the Direction of Abrasive Travel Are Designated by σ_1 and σ_2, Respectively

Authors' Closure

The authors would like to thank the discussers for their comments. In regard to Mr. Ogilvie's comments it should be pointed out that the authors were well aware of the necessity of measuring accurately the position of the diffracted lines. It was for this reason that a least-squares fitting of the intensity data were carried out on a punched-card computer using a minimum of twenty-four points to obtain the curve. Repetitive traverses of the same surface resulted in maxima which were within ±0.005 deg for 2θ. Chromium radiation would have been more satisfactory but at the time this work was being done this type of tube was unavailable. Admittedly, a two-exposure technique would have yielded more information but it is doubtful if the extra work involved could be justified.

We are grateful to Dr. Letner for presenting his results on tool steel. The fact that these data show a different sensitivity to work hardness is not surprising. Further work along this line can be expected to give rise to apparently anamolous results until the mechanism of producing residual stresses is better understood. The problem is not yet solved and future investigators would do well to be prepared to expect almost anything in the way of results. The problem is fascinating when one considers the potential for learning more about the mechanism of metal cutting itself.

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