Mechanical Behavior and Microstructure of Ausrolled Surfaces in Gear Steels

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Ausforming, the plastic deformation of heat-treatable steels in their metastable, austenitic condition, was shown several decades ago to lead to quenched and tempered steels that were harder, tougher and more durable under fatigue-type loading than conventionally heat-treated steels. To circumvent the large forces required to ausform entire components such as gears, cams and bearings, the ausforming process imparts added mechanical strength and durability only to those contact surfaces that are critically loaded. The ausrolling process, as utilized for finishing the loaded surfaces of machine elements, imparts high quality surface texture and geometry control. The near-net-shape geometry and surface topography of the machine elements must be controlled to be compatible with the network dimensional finish and the rolling die design requirements (Ref. 1).

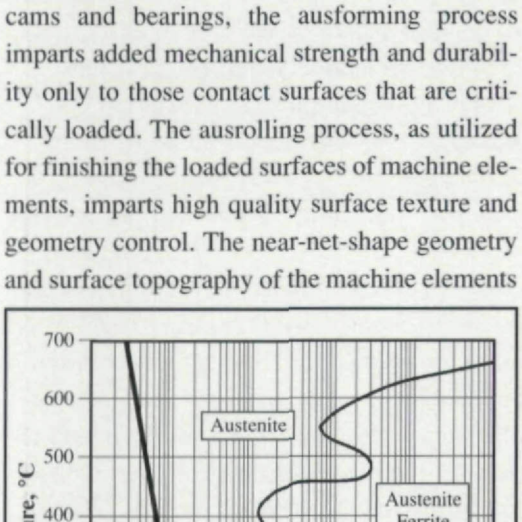

Fig. 1 — Thermomechanical history for ausrolling AISI 9310 steel with 1.0% carbon.

The proof testing of ausrolled gears poses unique challenges in assessing the changes wrought in gears by ausroll surface finishing. While hardness profiles within the gear teeth and the physical metallurgical features of the gears themselves can be readily ascertained, rolling contact fatigue, one of the most frequently noted reasons for gear failure, is most conveniently studied using standard rolling contact fatigue (RCF) specimens in a test of that genre (Ref. 2).

Outlined below are some of the recent results of studies at the National Center for Advanced Gear Manufacturing Technologies characterizing the microstructure and response of ausrolled gears and related model specimens. The gears examined are fabricated of AISI alloys 4023 and 9310, both case-carburized to 1.0% carbon (nominal). The former is a typical automotive transmission gear alloy; the latter is utilized in high performance aerospace transmissions.

Gear Processing

Ausroll processing can be visualized from the thermomechanical history shown in Fig. 1 (Ref. 3). The processing path indicated, with the time allotted to ausrolling at 232°C, would be equivalent to conventional marquenching if that part of the history were devoted to thermal equilibrating. Instead, the ausrolling imposed on the gear teeth imparts a shear strain of several hundred percent at the surface. After ausrolling, the gears are quenched into room temperature oil and tempered in the conventional manner.

Case Study No. 1
AISI 4023 Transmission Gear

The gear in question was a helical automotive transmission gear: it had a diametral pitch of 13.0, a helical angle of 27° and 59 teeth. The gear surface had been carburized to 1.0% carbon to an effective case depth of 0.027 inches, wherein the "effective case depth" is defined as the distance from the surface where the as-marquenched Rockwell hardness falls off to RCH = 50. AISI 4023 has an M_s temperature of 163°C, well below the processing environment of 232°C. Three types of processing were studied for this gear: 1) a conventionally processed gear (CP), wholly austenitized, quenched, tempered and surface ground; 2) a reaustenitized unground (hereafter denoted AUS) replica, induction heated to 925°C, quenched to 232°C, ausrolled, quenched to room temperature and tempered; 3) a reaustenitized unground replica (hereafter denoted MAR), induction heated to 925°C, marquenched to 232°C, maintained isothermally for a time increment equivalent to the ausroll process (20 s), quenched to room temperature and tempered. Fig. 2 compares the hardness profiles obtained by indenting along the tooth pitch line in the center of a sectioned tooth. Note that both reprocessed gears exhibit higher hardnesses in the near-surface regions, which must bear the maximum Hertzian contact stresses; the marquenched sample's increase over the conventionally processed gear may be because of the unground state of its tooth surface. The ausroll finished gear can be seen to have gained a full VHN 100, a notable 12% increase, and a possible strength increase of the order of 50 ksi at those hardness levels.

The residual stresses present in heat-treated gear teeth are capable of markedly affecting the service durability of the gear. Heat treating residual stresses are typically compressive, thereby offsetting by their magnitude the tensile bending stresses present at the tooth root. In addition, they algebraically reduce the subsurface shear stress or distortion energy states caused by Hertzian contact stresses; these components lead to gear failure by tooth pitting and spalling. Surface residual stresses in the plane

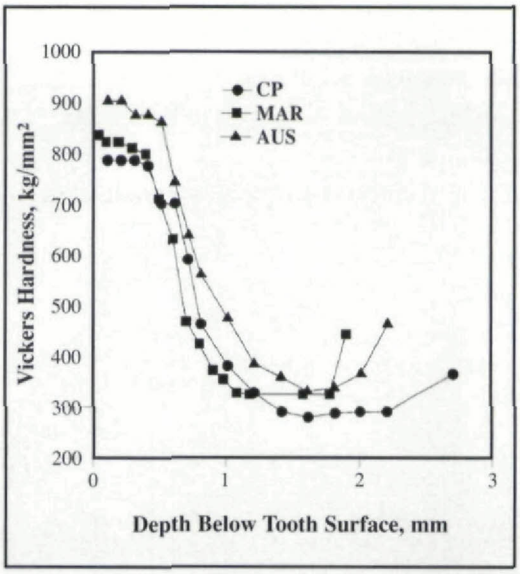

Fig. 2 — Surface hardness profiles in gear teeth as they depend on processing.

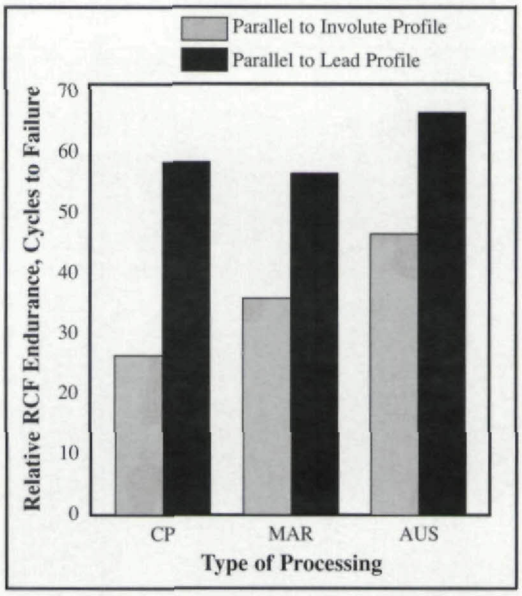

Fig. 3 — Surface residual stresses and processing in AISI 4023 helical gear teeth.

of the tooth surface at the pitch contact line were examined for the three types of processing—CP, MAR and AUS. Stresses were measured parallel to the involute profile (tip to root sense) and parallel to the lead profile (across the tooth thickness sense): Fig. 3 shows the results of the X-ray diffraction stress analysis. All three types of processing produce roughly the same residual stresses across the gear tooth, although ausroll finishing does show evidence of stresses that are 20% improved over the ground, conventionally processed gear. The other component, that which would most affect root bending stresses, is nearly 100% better; in addition, the two components of stress are more nearly the same magnitude after ausrolling, reducing the shear magnitude.

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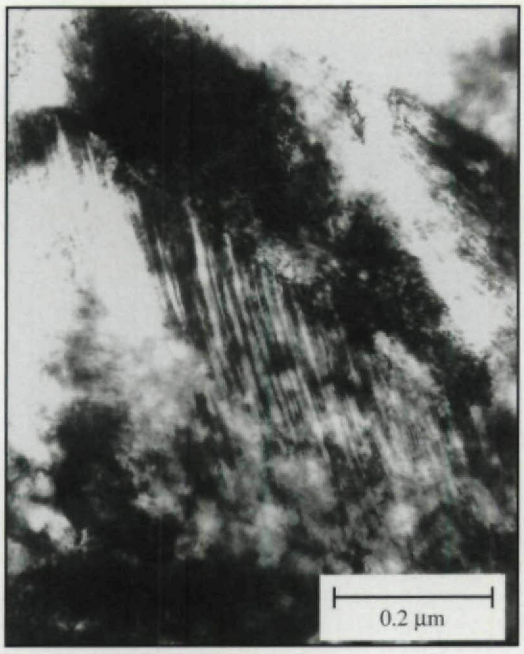

Fig. 4a — Ausrolled microtwins.

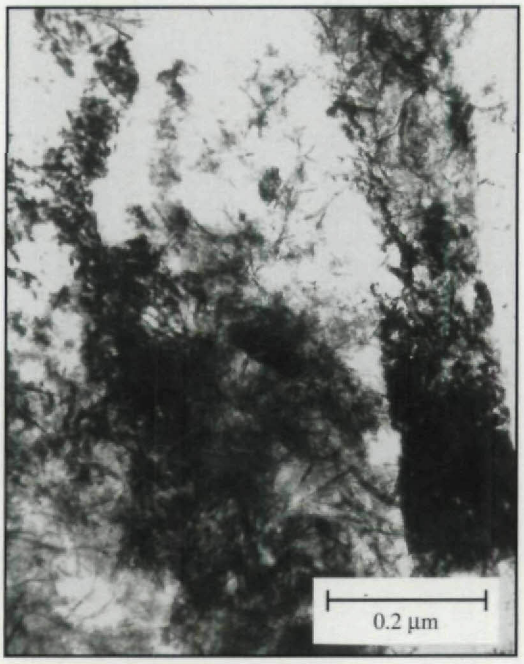

Fig. 4b — Ausrolled dislocations inherited by martensite.

Ausforming of any type induces signature microstructures (Ref. 4) that are not obtainable by any other thermomechanical processing; these, in turn, are responsible for the improved durability of the finished product. The ausrolled gear teeth were examined for the relevant microstructures, whose submicron nature can only be viewed using electron optical methods. Foils were electrolytically milled for near-surface regions of the teeth, and extraction replicas were taken of the tooth surfaces; both were examined by transmission electron microscopy. Fig. 4 is the result of the examination. 4a, 4b, and 4c show the observed microtwinning, inherited dislocation arrays and microcarbides (here, Mo_2C), respectively, that should be found in an ausrolled structural element.

Case Study No. 2
AISI 9310 Steel Endurance

The fundamentals of pitting and spalling failure as a result of rolling contact fatigue are most systematically studied with easily analyzed specimen geometries and standardized testers. AISI 9310 steel, with a carburized case of 1.0%C, was the gear material of interest. An alloy of this type can tolerate bending stresses of 700 MPa and Hertzian contact stresses of 2800 MPa in high efficiency aerospace transmission gearing. The specimens used in rolling contact fatigue (RCF) endurance testing were cylindrical in cross section, with a one-inch nominal diameter. They were either conventionally marquenched (MAR) or surface ausrolled in one of two modes. If ausrolled with a straight cylindrical die, which was forced into the specimen radially as they counterrotated, they were considered to be deformed in *line contact* (LC). If the die had a crown radius as well and was fed not only radially into the specimen, but along it axially, the deformation mode was idealized as *point contact* (PC). The main significance of the difference in rolling mode is that PC rolling induces a greater extent of plastic deformation than LC forming because the smaller contact area of the former carries the same rolling contact force as the latter (Ref. 5).

Fig. 5 demonstrates the extent of the case hardness profile formed by PC ausrolling and compares it to the profile obtained through conventional marquench processing. Both conditions were tempered at 150°C for two hours. Ausroll processing improves the surface hardness by 25%; moreover, the high hardness persists into the surface far beyond the expected states of maximum Hertzian contact stress. Fig. 6, which shows the relative rolling contact fatigue endurance of all processing states, reflects the enhanced hardness achieved through ausroll finishing, with the especially deep hardness zone of the PC ausrolling leading to an order of magnitude increase in RCF endurance.

Conclusions

Ausroll finishing of gears has been recognized as a highly cost-competitive operation for fabricating premier quality gearing normally ground to achieve requisite levels of finish and geometry control. Recent studies completed at the NCAGMT have clearly demonstrated that gear ausrolling imparts to the finished gear surfaces all of the property enhancements normally associated with ausforming technology in general. In particular, the tooth surfaces and subsurface regions exhibit greater hardness parameters that extend deeper beneath the surface than in identical cases conventionally marquenched. In addition to a stronger tooth surface, the beneficial residual stresses induced at the tooth surface are also larger than those found in conventional processing; in addition, they are not partially erased by finish grinding operations. Improved material response parameters and residual stress retention have, furthermore, been demonstrated to lead to better than an order of magnitude improvement in rolling contact fatigue endurance. Finally, microscopic examination of actual ausrolled gear teeth has established that the noted improvements in gear performance are indeed the result of the plastic deformation of metastable austenite, as the gear teeth contain the sense microtwins, inherited dislocation substructures and ultrafine precipitated carbides known to be responsible for ausform toughening. ○

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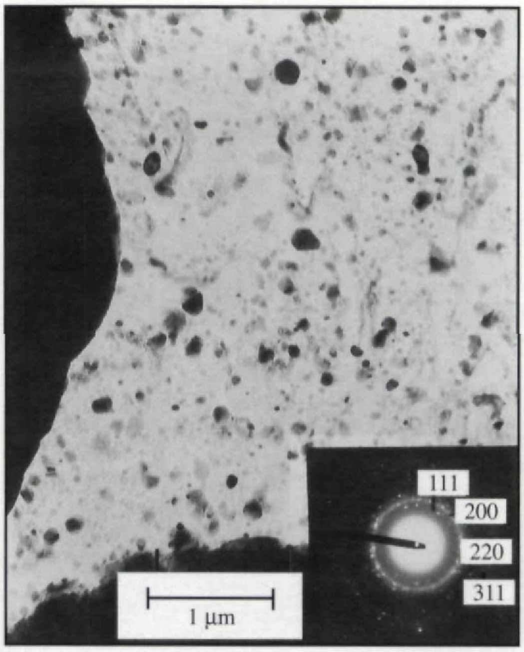

Fig. 4c — Microcarbides (Mo_2C) precipitated by ausrolling.

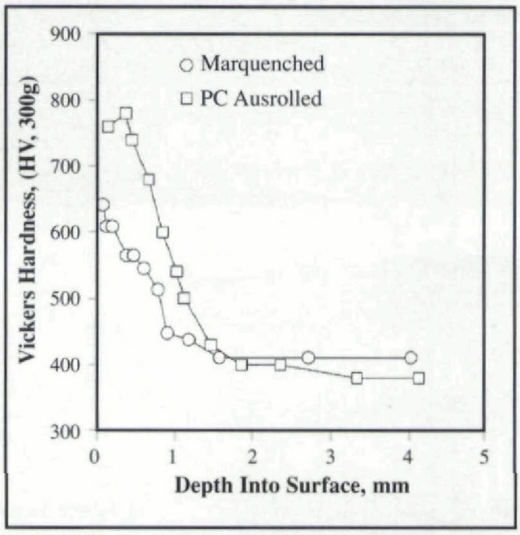

Fig. 5 — Subsurface hardness profile and processing in AISI steel with 1.0% carbon.

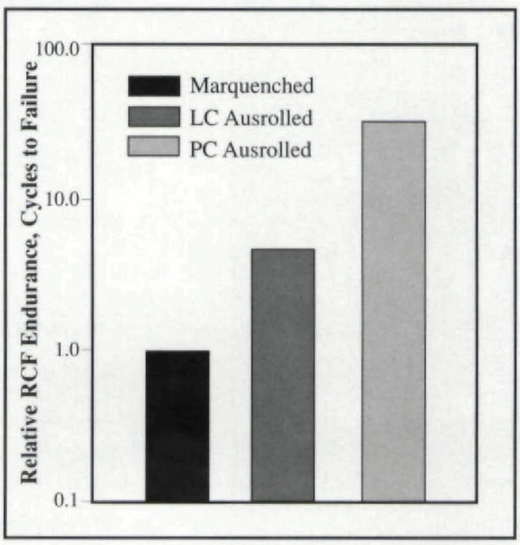

Fig. 6 — Relative rolling fatigue endurance and processing.