Considerations to the Surface Formation

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Abstract: Principles of metal cutting enable to explain formation of surface after cut. Surface after cut may refer either to removal by well–defined tool edge or to removal by abrasive. Concerning the former, surface is termed rather as "machined" surface, while the latter use often a terms as "surface finish", however, no clear dividing line between two terms mentioned do occurs. In metal cutting theories, four basic research fields have been established that deal with surface after cut, no matter whether machined surface or surface finish, as surface formation and surface layer, surface description, influence of technology on surface, surface integrity and surface in industrial service as well.

Keywords: removal schemes, surface after cut, surface layer properties.

Introduction

The term "surface" is peculiar not only to removal technology. Verily, such term can be found in another fields of science as physics, chemistry, electrical engineering, tribology, etc., and it always poses a portion of substance, regardless of being solid, liquid or particular, and such portion of substance provides a contact with other substance. In macroscopic vision, surface may represent either an envelope, or a cover; former and latter separate any substance from both environs and ambience. In microscopic vision, any surface is "an envelope", too, being expressed in terms of either micro–geometry, or micro–dimensions as for instance surface roughness, however, such "envelope" has a certain thickness, a surface layer. Surface layer may range within from 10^{-1} to 1 mm, and it results from various causes as mechanical processing (tools as forming, cutting, abrasive, etc.), vacuum deposition (CVD coating, etc.), metallurgy (corrosion–proof surface, wear–resistant surface, etc.), heat treatment (e.g. surface hardening), and so on. In chosen fields of science, the term "surface" refers either to any phenomenon as for instance skin effect in physics or to technology in wide meaning as:

- physics, as surface activity, surface–irradiation, surface tension, etc.,
- metallurgy as surface corrosion, surface–fusion alloying, surface etching, etc.,
- electronics as surface barrier, surface current density, surface leakage, etc.,
- tribology as surface loading, surface friction drag, surface delamination, etc.,
- vacuum deposition technology as surface coating, surface active agents, etc.,
- mechanical technology as machined surface, surface in joining process, etc.

Surface Formation and Surface Layer when Cutting

Surface formation and surface layer arise from sequence that occurs in chip formation comprising shear stress, friction, force, temperature and tool edge wear. While chip formation refers rather to certain phenomena, surface layer is any quantity resulting from sequence in such phenomena. Brief summary of phenomena in chip formation by well–defined cutting edge as:

i) shear angle
ii) chip shape, either continuous or discontinuous
iii) chip strain
iv) stresses that act at shear plane
v) stresses that occur at contact between tool flank and surface after cut
vi) "Ploughing effect" resulting from tool edge radius
vii) dimensions of BUE
viii) sticking length in chip/tool interface
ix) temperature being generated in heat sources
x) cutting conditions as speed, feed and depth of cut

are the causes that bring about both surface and surface layer to produce. Removal by any abrasive tool determines chiefly surface layer, following factors are being of great importance as:

i) micro–cutting, micro–ploughing, micro–rubbing
ii) micro–strain in front of abrasive grit
iii) "Ploughing effect" in micro–cutting
iv) mean size of abrasive grit
v) type of bonding agent or density of free abrasive
vi) mean count of abrasive grit producing surface after cut
vii) interactions in abrasive removal
viii) temperature distribution in surface layer
ix) heat flux density in grinding
x) cutting conditions as v_c; v_o, and a_e.

There are various formulae in removal with well-defined cutting edge enabling to express roughness *Rz* whereas following assumptions come in to consideration:

- material, which surface layer consists of, provides no strain
- tool edge is of being an ideal straight–line
- both workpiece and tool wedge render an ideal stiffness.

But no formulae conveying the *Rz* in removal by abrasive are available.

Calculation of *Rz* differs from that of measurement and such fact may be proved by each surface profile. Basic reasons, which bring about divergence between calculation and measurement of to *Rz* occur, are as follows:

a) Factors that result from material of workpiece:
   - final shape of chip being produced
   - sticking length that depends on both workpiece and tool material
   - plastic "flow" that occurs in cutting zone, a phenomenon depending on both "leaking" and "disruption" of layer to be cut

b) Factors that result from technology as:
   - chatter between tool edge and workpiece
   - irregularities in tool edge design, change in tool edge profile due to both tool wear and chipping
   - use of coolants and lubricants, etc.

Factors resulting from workpiece are of prevailing being and their categorisation entails the term "machinability of metals" to establish. Respecting the term mentioned above, the Fig. 1 gives appropriate explanation for surface roughness in machinability testing. But the factors by Fig. 1. are only one representation of numerous expressions for machinability. It means, moreover, machinability as a property provides no unit, such property is being expressed, either directly or indirectly, in terms of values having certain unit. Thus, surface after cut may be often realised as machinability by surface quality.

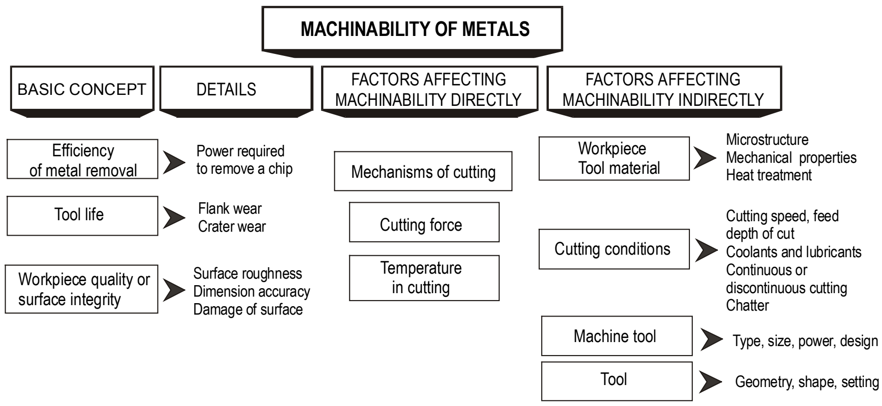

Fig. 1. Surface after cut in terms of machinability research

Formation of surface can be formulated either in terms of any model or experimentally; the former is shown in Fig. 2. An "overhang" of built-up edge (BUE) by Fig. 2(a) might have been an ideal representation, thus, both instability of BUE and changes in BUE dimensions are being carried over to surface after cut. Hence, real surface after cut provides statistical distribution of surface texture. But surface after cut by Fig. 2(b) may be produced in terms of adhesion. Sticking of chip within contact stops a flow of continuous chip while BUE is being charged by both primary and secondary shear stress. The former that occurs at shear plane and the latter at face of BUE bring about BUE from surface behind tool edge "to tear". Such "tearing", an accompanying phenomenon of surface formation, might occur with "seizure" at tool face. Because of resultant motion of tool edge, layer under seizure is removed and impressed into surface behind tool wedge, a consequence of BUE overhang. If cutting produces continuous chip by Fig. 2(c), surface is being generated through pure shear, and it means friction at tool flank that comprises penetration of tool edge radius known as "Ploughing Effect". Surface formation commences in front of tool wedge being subject to strain rate about 10^4 s^{-1}, a co–ordinate –0,15 mm in Fig. 2(c). To involve shear angle into formation of surface after cut, the approach by Fig. 2(d) explains surface formation regarding stress ratio. Deformed layer to be cut is subject to compressive stress, which transforms itself during chip formation into tensile stress. Having chip formation finished, tensile stress is never put back into zero but it is being transferred into surface layer as irreversible "residual stress". Residual stresses are of both tensile and compressive aspects resulting from temperature rise.

Having been studied various aspects of surface after cut; three common aspects were proved in surface formation as:

i) surface with debris of tearing resulting from BUE overhang, namely dull looks of a surface
ii) surface with debris of tearing, cleavage and shearing, namely semi–gloss of a surface
iii) surface produced by pure shearing, namely full gloss of a surface

Because of too vagueness in "dull looks" and "semi–gloss" or "full gloss" of any surface and no size for them by Fig. 3, the mechanisms i)÷iii) mentioned above depend on such factors as material of layer to be cut and cutting speed. Layer to be cut consist of defined metal and that is susceptibility BUE to originate. The materials termed as **a)** in Fig. 3 are of common carbon steels that have high response to the changes in both strain rate and immediate temperature due to shear, however, metals with body centred lattice are of susceptibility BUE to produce. The material **b)** has low response to both strain rate and temperature, thus, BUE is of microscopic size without tearing at surface after cut, a material with face centred lattice. The pure shearing runs any measured surface profile – most frequently the *Rz* – to that of calculation in theory. Pure shearing at cut surface is typical for one thing in high–speed–machining, and for another, it has been proved in cutting of hardened steel applying speeds above 90 m/min. Though such considerations are of generalised view, surface formation mechanisms by

Fig. 3 must be formulated basically as relationship explaining partly BUE formation as well as effect of cutting speed on cutting force.

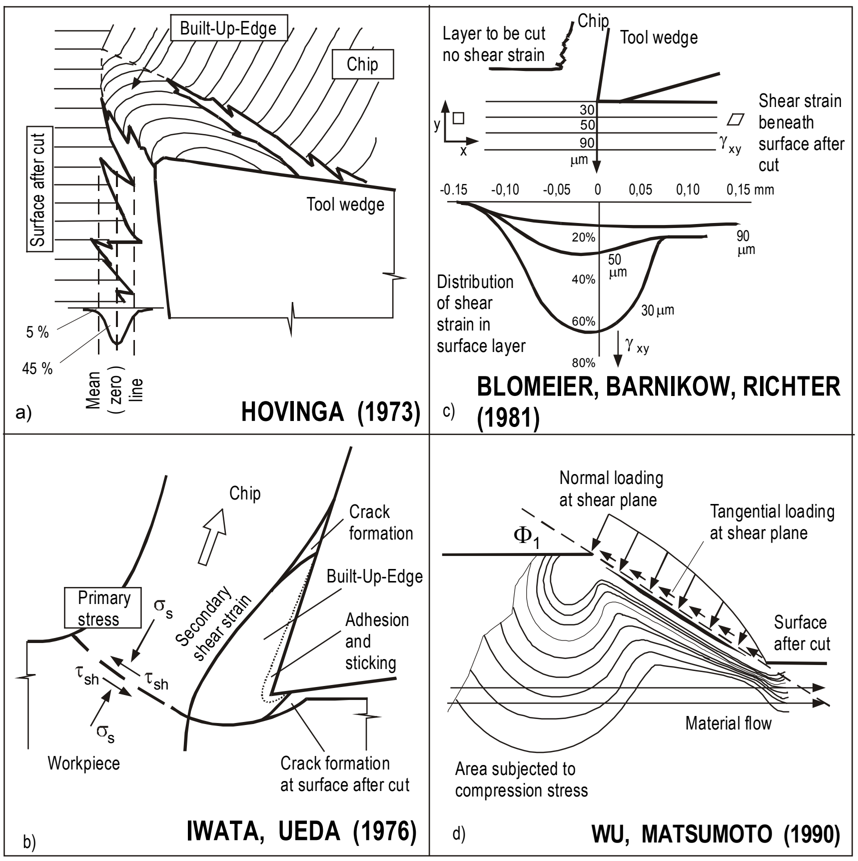

Fig. 2. Formation of surface after cut resulting from chip formation
(a) surface produced by overhang of BUE: (b) ductile damage of surface due to adhesion and BUE (c) shear strain in surface layer produced by friction of tool flank (d) compressive stress alongside shear plane due to chip strain

Each machining operation has an influence on surface layer h_I. Any surface layer shows different properties in comparison with that of basic metal, thickness of surface layer h_I results from mechanism of surface formation. Basic formula for h_I in orthogonal cutting was developed considering surface formation as slip–line field:

$$h_I = h\frac{1-\sin\Phi_1}{\sin\Phi_1} \qquad (1)$$

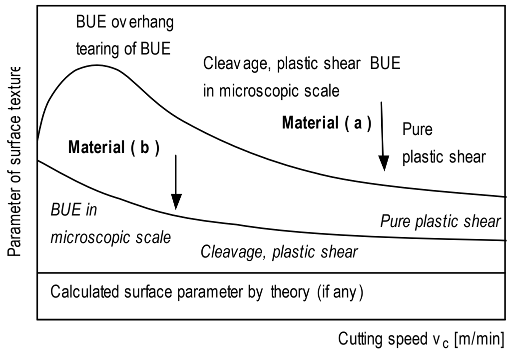

Fig. 3. Mechanisms of surface formation depending on changes in cutting speed

In machining by major and minor cutting edge as turning or milling, the formula mentioned above is completed by effect of angle of major cutting edge as follows:

$$h_I = f \frac{1 - \sin \Phi_1}{2.\sin \Phi_1} \sin 2\kappa_r \tag{2}$$

Generally, total thickness of surface layer h_I consists of:

i) absorption film 1 ÷ 30 nm
ii) sub-layer with plastic flow 1 ÷ 5 μm
iii) strained sub-layer 10 ÷ 500 μm
iv) sub-layer with span in residual stress: various data
v) basic metal, or bulk material.

Absorption film that provides nanometric dimension about 10^{-9} m results from immediate reaction of fresh surface with environs whereas vacuum–like friction might have been assumed, thus, oxidic film cannot be removed by any way. Sub-layer of plastic flow includes effect of maximum shear stress. To the newest findings, residual stress results mainly from chip formation in sequence:

- stress that loads layer to be cut in chip formation is of compressive type
- stress that brings about either chip curvature or chip breaking is of tensile type
- both phenomena of chip strain and chip fracture wherein the stresses are of irreversible nature
- residual stress is a difference between stresses that occur during sequence of chip formation and chip breaking (curvature), and as shown by Fig. 2(d), such residual stress is inferred into surface layer by wave–like effects.

Regarding temperature rise in chip formation, residual stress includes always certain portion that is activated by temperature flow into surface layer. In terms of chip formation, true residual stress in surface layer depends on:

i) shear angle
ii) coefficient of friction,
iii) temperature rise in surface layer
iv) yield stress resulting from tensile test data.

Residual stress is of best expression of any machined surface, no matter whether produced by cutting or by abrasive. Though residual stress may be expressed various exact procedures, it can be identified faithfully by means of experimental methods as gradual etching of surface layer and diffraction of roentgen rays in surface layer, as well. In compliance with data presented by various authors, residual stress may be characterised in common ways as follows:

a) dual change as sequence tension – compression – tension by Fig. 4(a):
b) simple change as sequence tension – compression by Fig. 4(b)
c) simple change as sequence compression – tension by Fig. 4(c)
d) change in sequence of stress occurs when $h_I \approx 0{,}15 \div 0{,}40$ mm depending on material of layer to be cut as shown by Fig. 4(c)
e) maximum residual tensile stress by Fig. 4 (a),(b) depend on mean temperature in cutting
f) residual stress in size depends on tool material used, as for instance ceramics insert, CBN grinding wheel, etc.

It must be noted that Fig. 4 incorporates neither no defined cutting conditions nor no tool materials; only representative feature of residual stresses is illustrated.

Surface Integrity and Surface Behaviour

Each machined surface is a part of engineering component made by any metal removal process, and each engineering component consists of definite set of surfaces. In assembly, an engineering component becomes a part of final product that carries out a certain role. Thus, machined surface comes into contact either with another surface or with fluid, accomplishing functioning of assembled device. In contact, in functioning or in loading, an arbitrary machined surface has its own functioning properties, or perhaps its behaviour that contribute to quality of assembled device, as for instance power transmission (clutch, brake, transmission, driving device, a i.), information processing (measurement device, video head ...), and so on.

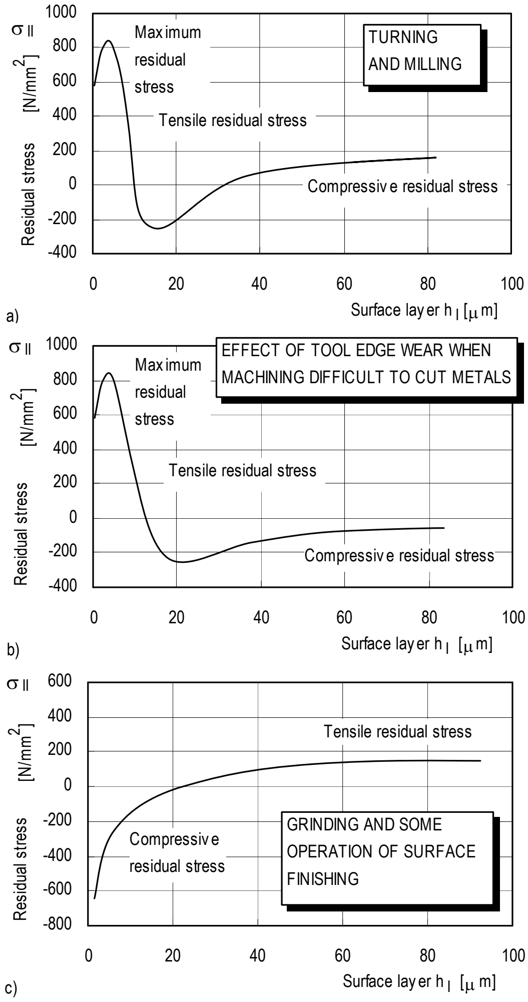

Fig. 4. Representative feature of residual stress in surface layer, distinguishing of residual stress

Relationship between surface layer and functioning is not fully perceived now. Machining operations provides for production of required final shape of component while its "life story" is studied by simple model ways rather in tribology as failure prevention, wear of surface by delamination, etc. A deficiency in feed–back between properties of surface layer and surface functioning lies in a fact that there are no pre–defined conditions in functioning of machined surface available, which would have been formulated in manufacturing. Tab. 1 shows sequence that formulates functioning of any component including factors determining functioning of any surface.

Tab. 1. Sequence that formulates functioning of machined surface

PROPERTIES EMERGING IN FUNCTIONING OF ANY SURFACE				
RUNNING CONDITIONS FOR SURFACES IN CONTACT	RUNNING PROPERTIES OF SURFACES IN CONTACT	SURFACE INTEGRITY	FORMATION OF MACHINED SURFACE	REMOVAL PROCESS OPERATIONS
❑ loading in service ❑ temperature and heat ❑ surrounding ❑ expected reliability ❑ expected life cycle	❑ friction ❑ wear ❑ fatigue ❑ corrosion ❑ stress corrosion ❑ adhesion, etc.	❑ Quantities expressing properties of surface layer	❑ effect of cutting force ❑ effect of stresses ❑ effect of temperature when cutting ❑ effect of BUE ❑ tearing, cleavage, pure shear	❑ tool material ❑ cutting conditions ❑ tool edge geometry ❑ used coolants or lubricants ❑ type of bonding agent

Surface integrity is an interdisciplinary approach that combines such fields as metallurgy, research in machinability, measurements and properties of surface layer as well. Surface integrity explains possible alterations in surface layer that may occur in production by cutting and abrasive, including effects of surface layer alterations on surface properties in service. Thus, surface integrity involves not only surface profile but also it includes subsequent phenomena being listed comprehensively in Tab. 2. Removal of layer to be cut – no matter whether by tool edge or by abrasive – does affect on surface layer while both residual stress and changes in micro hardness are only preferred quantities describing surface layer. Thus, surface layer is being characterised in terms of three next effects, namely, effects of environs in terms of chemistry, thermal effect due to surface formation, and finally, changes in electrical properties as well.

Tab. 2. Summary of main quantities expressing surface integrity

REMOVAL AND CUTTING	METALURGY	CHEMICAL EFFECTS	THERMAL EFFECTS	ELECTRIC PROPERTIES
❑ Surface defects ❑ Surface profile ❑ Micro hardness in surface layer ❑ Cracks at surface ❑ Residual stress ❑ Plastic strained microchips owing to cutting and abrasive ❑ Cavities and hollows at surface	❑ Phase transformations ❑ Grain size in microstructure ❑ Precipitation hardening ❑ Inclusions ❑ Twining in substructure ❑ Recrystallization ❑ Residual martensite ❑ Austenitization	❑ Intercrystalline fracture ❑ Intercrysalline corrosion ❑ Solubility of micro constituents ❑ Surface contamination ❑ Surface embrittlement ❑ Corrosion ❑ Stress corrosion	❑ Thermal agitation ❑ White layer when grindings ❑ Thermal stacking ❑ Thermal products	❑ Changes in conductivity ❑ Electrical resistance ❑ Magnetic field intensity ❑ Resistance losses

Conclusion

Implication for removal process for setting up of pre–defined functioning of any surface is not fully realised. No exact analytical methods are available, thus, effect of removal process is being studied only indirectly applying such testing as friction, wear, fatigue and corrosion. In accordance with Tab. 1, both corrosion under stress and adhesion phenomena are of importance when assessing surface functioning. Effect of both initial profile and surface integrity on surface functioning is not still expressed unquestionably and the same can be said for reliability of surface in service, too. A certain reason for it is that surface functioning depends not only on surface roughness but also on design of engineering component and material used in its fabrication. Hence, prediction of functioning of any engineering component throughout production technology, for instance reliability in service, lifespan, etc, must by studied comprehensively not only statistically but also in removal technology research.

Wear of two surfaces in contact is being explained by various approaches as theory of delamination, but, often neglecting "history" how surfaces in contact have been produced. In tribology, influence of removal was recorded due to wear progress following changes in coefficient of friction. Though polished surface has the smallest amount of wear at any arbitrary friction length, surface treatment by polishing is only one of factors determining surface functioning. If the same removal process is used, two different materials acquire different surfaces following different wear progress in contact. In tribological testing, coefficient of friction depends on removal technology. On the other hand, tool wear in milling does change coefficient of friction of machined surface that comes into contact.

In the field of wear of machined surface, certain knowledge has been settled, and this may be characterised as:

i) wear of any machined surface is affected by surface layer whereas surface integrity is being under influence of tool wear
ii) wear rate of any machined surface in contact depends chiefly on imperfections in surface layer
iii) strain in surface layer is determined mainly by negative geometry of tool rake.

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