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Workpiece Surface Integrity

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This chapter presents an analysis of workpiece surface integrity. The definition and material and mechanical aspects of surface integrity are discussed.

3.1 What Does Surface Integrity Mean?

The choice of manufacturing processes is based on cost, time and precision. The precision of a surface is usually based on two criteria: dimensional accuracy and surface roughness. However, another criterion has become increasingly important: the performance of the surface. The term *performance* has different meanings depending on the context but is mostly linked to fatigue, corrosion, wear and strength. It is usually assumed that performance is directly related to surface texture. The irregularities of the surface, especially valleys or grooves, induce stress concentrations that enable the plastification of the material and crack propagation. As a consequence, a smooth surface limits the risk of crack initiation. An example provided by [1] illustrates the influence of the surface texture generated by grinding on the fatigue strength (Figure 3.1). Curves 1 and 2 correspond to a standard grinding operation with conditions leading to so-called *gentle* operation. On the contrary, curve 3 corresponds to high-productivity operation with extreme cutting conditions. Curves 1 and 2 show that a higher surface texture (evaluated, for example, by the parameter Ra) is responsible for the decrease of the fatigue strength. It also shows that, depending on the orientation of grinding marks (surface texture effect), the fatigue resistance is different. Note that the surface roughness parameter Ra alone is not able to describe resistance to fatigue. Additional parameters such as Rku, RSk, *etc.* are more relevant.

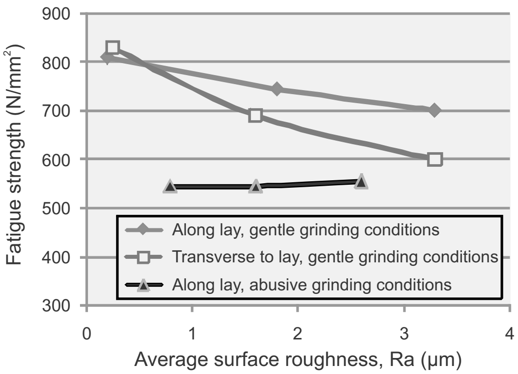

Figure 3.1. Influence of a grinding operation on the fatigue strength

However, the surface roughness criterion does not explain the results obtained for curve 3, which appears to be very poor. Moreover, with this manufacturing procedure, the surface roughness does not seem to influence the fatigue strength. It is clear that the sub-surface is as important as the surface texture. Especially, the microstructure and the residual stress state are strategic parameters. Indeed, this manufacturing procedure has probably induced dramatic modifications of the sub-surface, which is a very common problem in grinding, as described by a large number of publications [2–6].

Another investigation [7] has shown that the effect of the mechanical state of the sub-surface (the residual stress state) has much more influence on the fatigue resistance of a piece if its surface roughness is below a certain limit. This trend is also confirmed by [8]. This underlines that external parameters and internal parameters are both strategic, depending on the context of application. For that reason, the term *surface integrity* was introduced, which aims to describe the state of a surface (from external and internal points of view) with regard to its potential performance. The oiginal definition [9] of this term is "the inherent or enhanced condition of a surface produced in a machining or other surface generation operation". After some years of scientific works on the subject, a new definition has been proposed [10]: "the topographical, mechanical, chemical and metallurgical worth of a manufactured surface and its relationship to functional performance".

A surface can be defined as a border between a part and its environment. One particular piece belonging to a mechanical system has several surfaces. In common practice, engineers design pieces to satisfy a list of criteria in relation to the function of each surface. Some surfaces have mechanical contact with another part, whereas other surfaces just make contact with air or oil, *etc.* As a consequence, the specification of each surface is different depending on its function:

- Mechanical functions (capability of carrying mechanical loads)
- Thermal functions (heat resistance or temperature conductivity)

- Tribological functions (surface interaction with other surfaces: rolling, sealing, sliding, *etc*.)
- Optical functions (visible appearance, light reflection behaviour)
- Flow functions (influence on the flow of fluids)

From a global point of view, surfaces have to support: chemical attack, tribological solicitations, mechanical pressure, heat transfer, *etc*.

A surface is usually composed of several layers that differ from the bulk material in composition and structure. The surface composition is schematically illustrated in Figure 3.2. Indeed, as soon as a freshly machined surface is exposed, it will oxidize and adsorb. The adsorbate surface consists of water vapour and hydrocarbons from the environment (air, cutting fluids, *etc*.). Beneath this layer, there is an oxide. Its thickness can remain stable (for example, in the case of stainless steels or aluminium alloys) or may continue to grow with time (for example, in the case of low-carbon unalloyed steels). Beneath the oxide layer is the strained and metallurgically altered region (by the manufacturing processes), which is several orders of magnitude greater than the depth of the previous layers, several tenths of a millimetre.

The aircraft industry was among the first to consider the surface integrity of their pieces, since the consequences of a breakage are always dramatic from a human and economical point of view. Such an industry has a double objective: designing aircraft with a minimum weight (*i.e.*, with pieces having small sections) and producing pieces with a high degree of safety. Moreover, an additional objective is increasingly becoming important: economical competition, which induces pressure on production costs and obliges factories to produce more rapidly. The combination of these three objectives (thin, fast and safe) makes this job very difficult. In such a context, the surface integrity of their pieces is of primary importance.

Such objectives are also becoming increasingly critical in other industries, such as the automotive industry, because car manufacturers are engaged in a race with two objectives:

- weight reduction in order to reduce gas consumption,
- increase of engine power in order to satisfy pollution criteria, which leads to increased mechanical stresses that has to be supported by the pieces in the power transmission

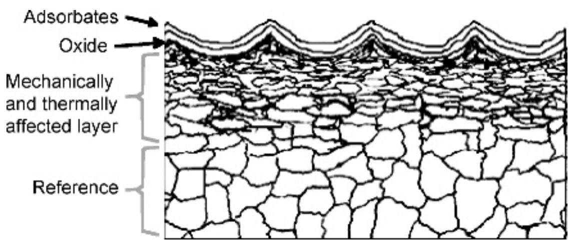

Figure 3.2. Schematic section of a machined surface

	Surface physical properties					
Failure cause	Yield stress	Hardness	Strength	Residual stress	Texture	Micro-cracks
Plastic deformation	++	++				
Scuffing/adhesion		++				
Fracture/cracking	+	+	+			+
Fatigue				++	++	++
Cavitation		+				+
Wear		++			+	
Diffusion					+	
Corrosion				+	++	++

++ *: large influence*

+ *: potential influence*

Figure 3.3. Interrelation between failure modes and surface properties

These two contradictory objectives give increasing importance to the impact of the surface integrity on the reliability of cars.

All companies manufacturing mechanical products have experience of a component breaking linked either to a poor design or to a manufacturing problem. Each company has developed some home-made specifications and the corresponding manufacturing procedure to ensure the reliability of their products. However, they have often carried out little investigation in order to correlate these specifications, their manufacturing procedures and the performance of the surfaces. Most of the time, they use the solutions developed in previous applications. When a problem occurs or when a serious change is introduced (for example, a new material), companies try to find a solution quickly without having all the information allowing solutions to be predicted reliably.

Some authors [10–11] have proposed a connection between the properties of the surface, the failure mode and the performance, as reported in Figure 3.3.

3.1.1 Link Between Surface Integrity and its Manufacturing Procedure

The evaluation criterion of a process depends on the functionality of the machined surface and on the economic efficiency of the process. Usually, the last machining operation is always suspected of being responsible for a breakage. In fact, it is very important to bear in mind that the state of the sub-surface is the consequence of the superposition of the individual stresses induced by all manufacturing sequences: from the purchase of the raw material to the superfinishing operation, including the machining in the low hardness state, the heat treatment, the semi-finishing operation in the hardened state, *etc.*

As an example, in the case of a synchrogear, one manufacturing procedure is illustrated in Figure 3.4. Three typical causes of failure are due to:

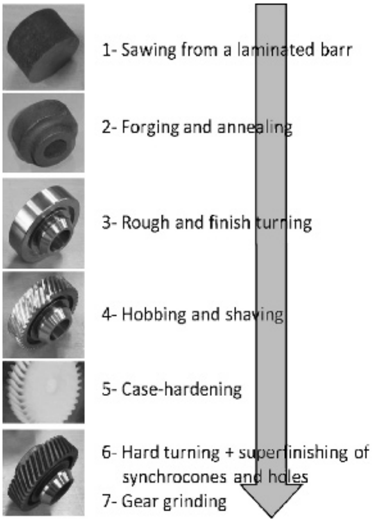

Figure 3.4. Manufacturing procedure of a synchrogear

- Poor surface texture generated by the super-finishing operation. This problem may lead to a breakage of the synchrocone due to the torsion supported by this surface when changing the speed of the gearbox.
- Poor grinding operation of the teeth (bad surface texture and/or a microstructural modification associated with tensile residual stresses). This problem may lead to the breakage of a tooth or to a rapid wear of the surface.
- Poor heat treatment. If the cooling rate is too high, phase transformations occur in the external layer, whereas the cooling of the bulk is not so rapid, which leads to strong internal stresses during a short period. If stresses exceed the strength, cracks may occur (Figure 3.5).

However, the hard turning operation of the synchrocone is potentially also a cause of breakage, since an abusive hard turning operation, involving an excessive cutting speed and/or worn tool, may induce microstructural modifications and tensile residual stresses, which may lead to fracture initiation in the sublayer. In deed, the final super-finishing operation is only responsible for the surface texture and for the initiation of a compressive state in the external layer (~10 µm), whereas hard turning can modify the microstructure deep beneath this layer [12, 13].

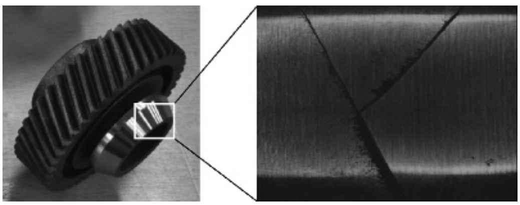

Figure 3.5. Cracks induced by the quenching of a gear

Another typical example concerns the fatigue resistance of crankshafts [5]. Some authors [14] have shown that the ultimate roller burnishing is able to delay the appearance of cracks in grooves and as a consequence improve the fatigue resistance. However, the final result depends strongly on the heat treatment made by induction, which is a very sensitive process [15].

Each machining process has his own signature on the surface integrity, since it removes layers from a workpiece with its specific mechanism. However, this signature has a spectrum of characteristics depending on the conditions of application (cutting conditions, lubrication, wear of cutting tools, *etc*.); for example, a gentle hard turning operation will generate a very smooth surface (Ra ~ 0.3 μm) and will induce compressive residual stresses, whereas an abusive hard turning operation will induce tensile residual stresses associated with microstructural modifications [12]. The main difference between these two configurations comes from the heat, strains and strain rates induced by the machining process.

As a consequence, it is impossible to give detailed informations about the surface integrity induced by each type of machining processes whatever the conditions of applications used by any end user. It is only possible to provide some general trends about the usual surface integrity observed in some current applications.

The most efficient method for designing/manufacturing companies is probably to characterize the surface integrity of each pair machining process/work material commonly applied in their shop floors. As shown previously, they should also consider this approach to validate new machining conditions (for example, a new cutting tool that is theoretically more productive or more wear resistant or a new cutting fluid that is more environmental friendly, *etc*.) and to optimise their production conditions with the best combination of productivity, wear and surface integrity parameters. Moreover these data would enable engineers to select the best machining process for a new application.

3.1.2 Impact of the Surface Integrity on the Dimensional Accuracy

Each machining sequence introduces a modification of the stress state of the piece. It produces relaxation inherent to the layer removal (modification of previous residual stresses) and induces additional stresses. Each production step can influence distortion by generating a distortion potential which is inherently stored in the workpiece and passed to the subsequent production steps. According to [16], distortions are influenced by:

- Steel production
- Metal forming
- Cutting
- Heat treatment
- Fine finishing

Between two manufacturing sequences, the surface residual stresses are balanced by bulk residual stresses of the opposite sign. Sometimes, if machining is only carried out on one side of a component with a large amount of material removal, the residual stresses can result in considerable distortion. Figure 3.6 shows the example of a semi-cylindrical piece produced with the following manufacturing procedure:

1. Rough machining from a monolithic bloc
2. Annealing heat treatment, which is supposed to cancel all previous residual stresses
3. Finish machining in order to obtain accurate dimensions. This is supposed to induce some residual stresses in a thin external layer: a few tenths of a millimetre. However these stresses are supposed to be negligible compared to the one induced in the next step
4. Cold forging (3 mm of plastic deformation), which induces strong residual stresses in the bulk material due to the plastification
5. Rough milling of a 20 × 20 mm slot

Figure 3.6 shows the residual stress state after the forging operation (following [17]). It appears that the residual stress level is very high (~ 800 MPa Von Mises stress). After the rough milling operation, a large distortion of the workpiece, due to the relaxation of the residual stresses, is observed: ΔA =1.35 mm.

Figure 3.7 shows another basic example typically observed after the machining of a bar in its drawn state (following [17]). The bar contains a large gradient of residual stresses. The milling operation modifies this field of residual stresses and leads to great distortion (more than 1 mm).

Another standard case study, *i.e.*, the manufacturing of a bearing cage, has been investigated in depth by [16], since it is a typical thin part, which is especially sensitive to distortions.

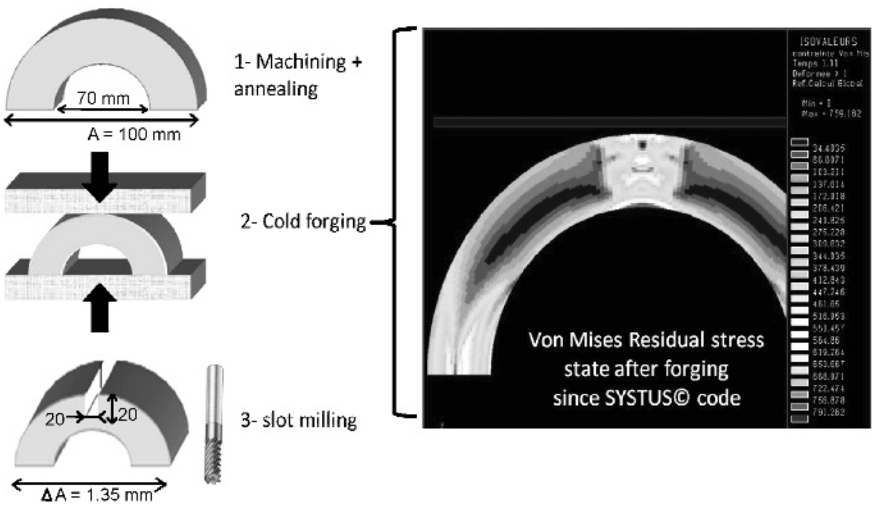

Figure 3.6. Distortion of a part due to relaxation of residual stresses

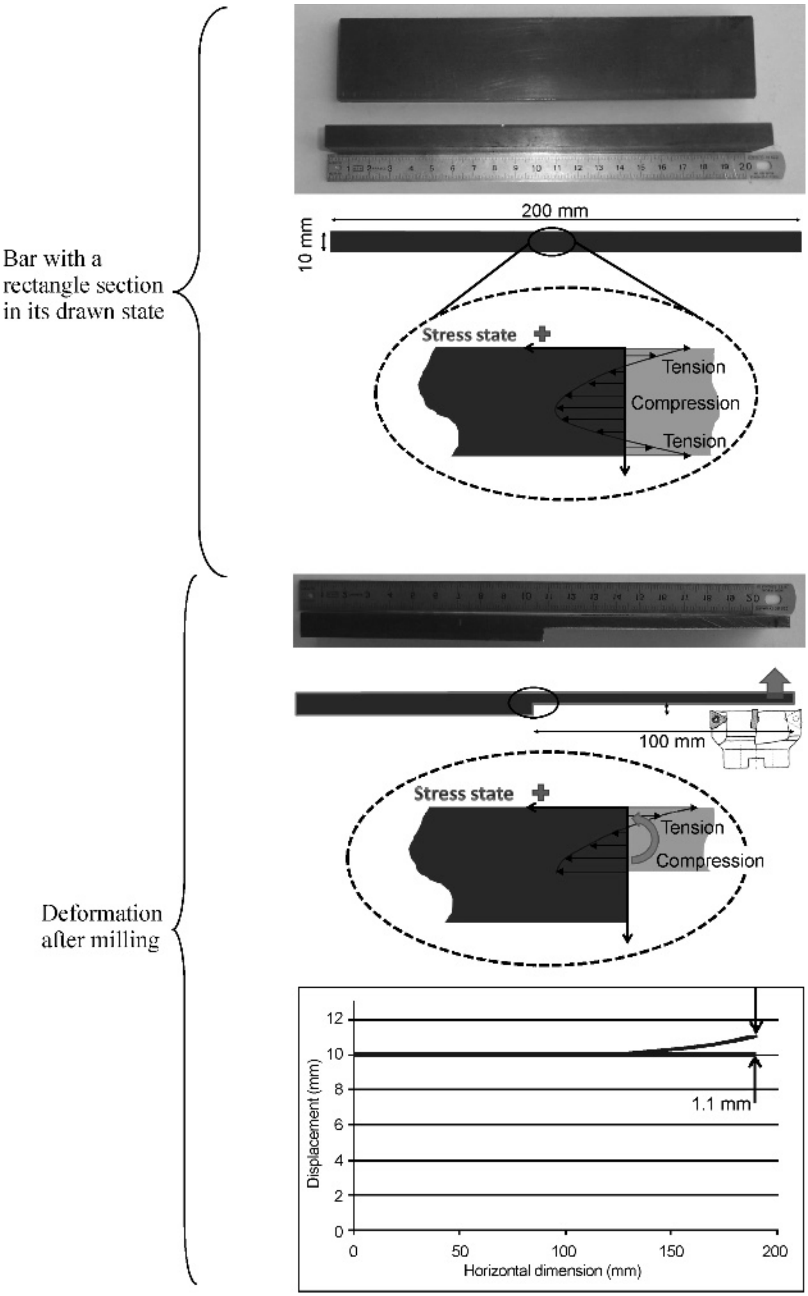

Figure 3.7. Deformation of a bar due to relaxation of residual stresses

It has been shown [18] that the residual stress state of the initial Al7440 T7651 block for aircraft structures can significantly affect the part distortion in the roughened stage (95% of chip removal), whereas the introduction of residual stresses in the finishing stage of thin sections also has an important effect on the case of thin structures.

Some authors have tried to make a link between the superposition of residual stresses produced by the various sequences of a manufacturing process and the relaxation induced by machining. For example, [19] has investigated the modification and evolution of the residual stress field, originating from welding, after chip-forming machining, such as milling and cutting.

3.1.3 Impact of the Surface Integrity on Fatigue Resistance

Residual stresses can have a wide variety of profiles depending on the manufacturing procedure. The magnitude and sign of the residual stress will have a significant effect on functional performance. A common idea is to prefer compressive residual stresses in the external layer because they tend to close surface cracks. However the fatigue resistance properties of a surface depend on the thermo-mechanical loading supported by the surface (bending, tension, torsion, rolling, *etc.*), for example, it is preferable that a rolling contact has a peak of compressive residual stresses in the sublayer, where the shear stresses are maximum. This would limit the pitting fatigue in some typical applications such as bearings, camshafts, *etc*. As an example, it has been shown by [20] that rolling fatigue of bearings is improved when hard turning is used instead of grinding. This improvement is explained by the large peak of compression in the sub-surface. In parallel, [21, 22] have shown that hard turning operations managed in gentle conditions with new tools can increase the rolling contact fatigue by up to six times compared to the same operation made with a worn tool. This result is explained by the modification of the residual stress profile and by microstructural modifications.

If a part is submitted to a bending loading (similar to a standard four-point bending test in a laboratory), the external residual stress state is of great importance. As an example, [7] investigated the influence of the hard turning process on the fatigue resistance of the case-hardened steel 16MnCr5 (AISI5115). It has been shown that a hard turning operation managed with a new tool leads to compressive stresses in the external layer and to high fatigue resistance. This fatigue resistance is significantly worse with flank wear of the c-BN insert.

A similar trend was observed for various applications by [23]: the fatigue resistance in four-point bending tests is directly correlated to the external residual stress state. A compressive residual stress is beneficial for fatigue resistance in the case of a 30NiCrMo16 bainito-martensitic steel manufactured by finish turning, or in the case of 7075 T7351 aluminium alloy manufactured by finish peripheral milling. On the contrary, a TiAl6V manufactured by finish turning, or a 7075 T7351 aluminium manufactured by face milling, do not seem to be sensitive to this parameter, but to the surface roughness only.

In a different context, [24] investigated the influence of the honing process on 12%Cr stainless steels and on Hastelloy X, showing that this process leads to compressive stresses in the surface and to a very smooth surface. Rotation bending fatigue tests and pulsating push–pull fatigue tests have shown a great improvement of the resistance compared to a shot peening operation. However this improvement was even better in an aggressive atmosphere (water + sodium chloride) than in air, which proves the improvement of the resistance against stress corrosion.

Finally, the effect of the application of a coolant during a machining operation should not be neglected [25]. The tribo-physical and tribo-chemical interactions between the cutting tool, workpiece, metalworking fluid and surrounding medium have an influence on the properties of the resulting surface. Defects can be generated by adsorption and reaction layers on the machined metal surface: dirt, oils, greases as well as residues from the machining process. In a study of the machining of 42CrMo4 steel the effect of various metalworking fluids on the results of the gas nitriding process used for surface hardening were reported. It was observed that using sulphur and phosphorus additives in the cutting fluid may lead to a decreased surface hardness after gas nitriding, which leads to a dramatic wear rate.

These complementary examples show that the correlation between the fatigue resistance of a part and its surface integrity depends strongly on the loadings supported by the surface (thermal, mechanical, chemical) and on the material and on the manufacturing process. It is very difficult to define universal ideas in this area.

In this chapter, surface integrity will be more detailed regarding its sub-surface state (metallurgical and mechanical states). Readers interested in information about the influence and characterization of surface texture are referred to [10, 26–28].

3.2 Material and Mechanical Aspects of Surface Integrity

Residual stresses are defined as mechanical stresses in a solid body, which is currently not exposed to forces or torques and which has no temperature gradient. The superposition of the residual stresses induced during the material manufacture and machining operations leads to the final residual stress distribution.

3.2.1 Mechanisms Leading to Material and Mechanical Modifications in Machining

In order to predict the performance of a surface, it is of great importance to characterize the signature of machining procedures in the field of material and mechanical state. A signature depends mainly on the combination of the mechanical, the thermal and the chemical loadings applied by the cutting process on the surface and on the sub-surface. Most of the processes are a combination of the three generating mechanisms. Just some processes can be clearly attributed to one single mechanism. As an example, electro-discharge machining (EDM) is clearly a thermal process, since there is no mechanical contact between the workpiece and the electrode. The temperature increases to the melting temperature because of electrical discharges, and then the material is solidified by the cooling effect of the dielectric. On the contrary, electro-chemical machining (ECM) is clearly a chemical process. It is not able to induce any residual stress in the material, nore any microstructural modifications. For other machining processes, the classifications are not so clear. It is evident that any processes inducing large strain and strain rates will also induce some heat due to the plastic deformation of the material and a large quantity of heat due to the friction between the cutting tool and the material. Modification of the mechanical state in the surface and sub-surface occurs systematically, inducing residual stresses. Depending on the amount of energy, the temperature reached and the time of exposure, microstructural modifications may also occur in an external layer. A typical consequence in steel machining is the observation of so-called white layers, so named as they appear white in micrographs after etching. These are due to short-term metallurgical processes that occur under specific cutting conditions. Based on this statement, it is evident that each machining process involves more or less plastic deformation and friction, resulting in a large spectrum of consequences on the material and mechanical states of the machined surface. Moreover, even a defined machining process has a wide range of thermo-mechanical effects, since cutting tool geometries, cutting conditions, lubrication and tool wear are very sensitive parameters on this aspect of surface integrity.

Residual-stress-generating mechanisms can be simplistically represented by four models:

- Plastic deformation induced by mechanical load: the external residual stress is compressive because the surface layer is compacted by some form of mechanical action. There are no (or very limited) heating effects. This also applies to some other processes such as roller burnishing.
- Plastic deformation induced by thermal load (without phase transformation): the external residual stress is tensile because the surface expands greatly during heating, whereas the subsurface does not. The external surface is plastified by compression. When cooling, the external surface tends to recover its position, which is no longer possible due to the plastic deformation, leading to a tensile state.
- Plastic deformation induced by phase transformations: the residual stress may be caused by a volume change due to a phase transformation. If the phase change causes a decrease in volume (for example, the transformation of martensite into austenite), the surface layer wants to contract but the underlying bulk material will resist this. The result is that the surface layer is under tension, whereas the sub-layer is under compression. If the phase transformation causes an increase in volume (for example, the transformation of austenite into martensite), the residual stress will be compressive. This is the case with conventional heat treatment of steel. It also applies to nitriding or case hardening, in which the volume increase is caused by diffusion.
- Thermal/plastic deformation: in practice, a combination of the previous mechanisms occurs, leading to either more compressive or tensile stresses.

3.2.1.1 Mechanical Plastic Deformation

Plastic deformation occurs when the stress exceed the elastic limit, inducing strain hardening. A plastic flow occurs, which may lead to cracks. Depending on intensity and on the contact area, the mechanically affected zone can have various thicknesses. In some extreme cases, grains are so distorted that the structure is not observable in micrograph analysis and appears white after etching. Processes such as burnishing, reaming, honing and broaching produce large strain hardening with a limited amount of heat due to either low friction phenomena or low velocities. Processes such as turning, milling and drilling also include large plastic deformations at low cutting speeds, but thermal effects become predominant in high-speed cutting.

In mechanically dominated processes, the hardness constantly increases from bulk to surface, whereas in thermal processes this is not the case.

In order to discuss the mechanical impact of a cutting process, a turning operation will be described. As shown in Figure 3.8, mechanical effects are due to the pressure applied by the rake face and by the cutting edge radius. The workmaterial is plastically deformed by compression in front of the cutting tool, whereas it is submitted to tension behind the cutting tool. Figure 3.8 shows the compressive

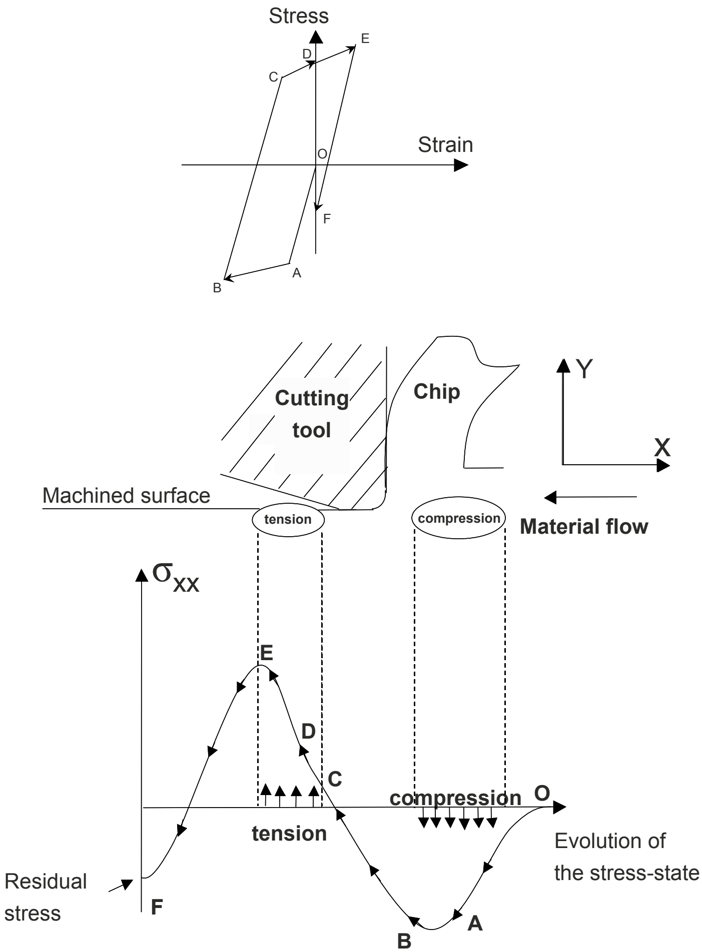

Figure 3.8. Principle of residual stress creation under a pure mechanical load in cutting

zone OAB and the tensile zone CDE. Finally, when the cutting tool has moved far from the surface, the unload zone EF appears. When the machined surface is not exposed to any forces, it appears that compressive residual stresses remain at the surface. Of course, to maintain the mechanical equilibrium of the system, tensile stresses exist in the sub-surface [29, 30].

If the plastic deformation is very high, the material may become so deformed that it is not possible to discern any microstructure. The external layer appears as white in a micrograph. If such so-called white layers remain during service operation, failure may occur by an excessive additional stress.

3.2.1.2 Thermal Effects Without Microstructural Changes

Thermal effects have a totally different action compared to mechanical effects. When crossing the primary shear zone in front of the cutting tool and when rubbing the clearance face of the cutting tool, the future machined surface is submitted to an intense heat flux (Figure 3.9). If the mechanical effects and the microstructural modifications are neglected, the machined layer is either in compression or in tension, depending on the expansion coefficient. Most of the time, for metals, the expansion coefficient has a positive value. As a consequence, in the zone OAB (Figure 3.9), the future machined surface is in compression. The zone BCD corresponds to the cooling of the surface by means of the bulk material or of the environment (air or coolant). During the exposure to intense heat fluxes, high temperature gradient exists, which may lead to a local plastification of the workmaterial. When the surface is returned to a steady state at room temperature, tensile stresses remain at the surface. Consequently compressive stresses exist in the sub-surface [31].

3.2.1.3 Thermal Effects with Microstructural Changes

As described previously, intense heat fluxes are applied on the machined surface in the primary shear zone and in the rubbing zone. A thermal load has a delayed consequence, since the heat transfer depends on the thermal properties of the material and of the cutting tool. This also depends on the heat exchange coefficient at the tool–work material interface. Anyway, the temperature can rise very quickly in the vicinity of the heat sources, whereas it takes time to raise some micrometres further in the sub-surface. For a defined amount of energy, microstructural modifications can occur. These changes are completely different to the one typically observed in the steady-state situation. Indeed, the heating rate and the cooling rate can be very high, which limits the possibilities of atoms diffusion and reconstruction of crystals. Example, in hard turning, a typical heating rate is around 10^6 °C/s [32, 33], whereas a typical cooling rate in grinding is around 10^3 °C/s [34, 35].

The case of the machining of treated steel will be more detailed in the rest of the section since it is the most common situation that has been largely discussed in the scientific literature [36]. In this context, the metallurgical modifications are often called white layers. This term refers to surfaces appearing white in a micrograph analysis, which means that its microstructure cannot be distinguished due to either a very thin structure or a lack of chemical reaction of the structure with the chemical reactor used (typically *nital* for steels). A white layer is often accompanied by

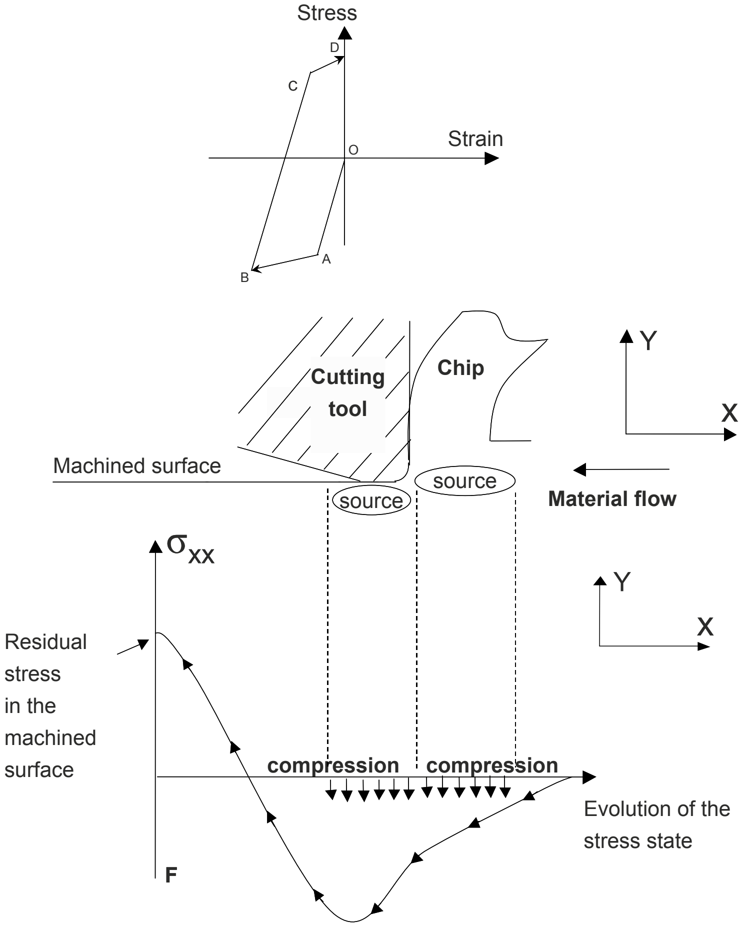

Figure 3.9. Principle of residual stress creation under a pure thermal load in cutting

untempered martensite and retained austenite with a very fine structure. Their hardnesses are usually higher than conventional martensite. The thickness depends on the quantity of energy (density and duration). White layers have been associated with grinding for many years because the energy density is very high in this process compared to other processes such as turning. So it is very easy to get white layers with inadequate grinding conditions, in contrast to with turning. Moreover, the surface appears in some extreme situation as burned (brown coloured) due to the oxidation of the surface besides the presence of coolant, which is almost impossible to obtain in any other processes even in critical conditions. White layers are assumed to be detrimental for the service performance of a piece. Abusive grinding operation can reduce the fatigue endurance limit of a piece by 40% [10]. The hard brittle layer can initiate cracks and is usually accompanied by tensile residual stresses, which facilitate the crack propagation.

In conventional heat treatment, TTT diagrams are used for the prediction of the phase transformation. However such diagrams suppose that the duration is long enough to obtain a homogeneous structure. In the case of machining processes, the heating rate is very high. As a consequence, in conventional heat treatment, the temperature necessary to reach similar transformations are much higher. Figure 3.10 shows how the heating rate modifies the limit Ac1 and Ac3 of an hypereutectoid steel. It appears that a tempered state enables the modification to occur at much lower temperatures and after a shorter duration. It is clear why hardened steel has a tendency to undesirable transformations even at a heat impact for a short time. After long heat treatment durations, transformations can take place via nucleation, crystal growth, diffusion, *etc*. At a definite critical heating rate no further shifts of the transformation lines Ac1 and Ac3 can be observed. In high-speed cutting, a diffusionless transformation occurs, which means that recrystallisation of different crystal modifications without atomic diffusion processes happens.

In short-time heat treatment processes, the quenching rate can be reached by rapid heat dissipation to the cooler core of the part or to the lubricant, so that a lasting heat impact on the newly generated martensite is suppressed. Hence, a very fine-grained structure is formed, which in micrographs can appear as white due to the limit of resolution of a light optical microscope. This induces the rehardening of the external layer. This specific performance is utilised in short-time heat treatment methods such as induction and laser hardening to carry out a local surface hardening while supplying relatively low quantities of energy.

When the amount of heat is higher due to a longer exposure or to a more intense heat flux, the sub-layer cannot evacuate rapidly the heat flux coming from the surface. Then the sub-layer may be tempered, causing softening. This layer is a so-called overtempered martensite structure (appearing black in the case of steel etched by nital), which has a lower hardness than bulk material made of conventional martensite (Figure 3.11). On micrographs, no clear transformation line can be seen between the heat-affected layer and the bulk.

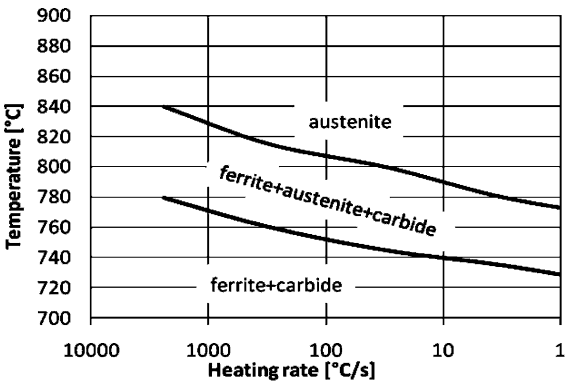

Figure 3.10. Influence of the heating rate on the TTA diagram for a hypereutectoid steel Cf53

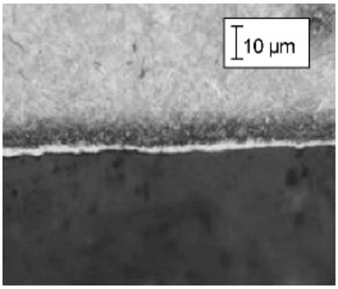

Figure 3.11. Microstructural modification induced by a hard turning operation on a 27MnCr5 case-hardened steel [12]

When this amount of heat becomes even higher, additional microstructural transformations (with diffusion) mavy occur, leading to untempered martensite and retained austenite, in parallel to an oxidation of the surface (burned surface). Such layers appear as white in micrographs, since austenite is not sensitive to nital etching.

Beside the aforementioned phase transformation, which occurs depending on the time–temperature profile and on the specific material properties, the thermal expansion caused by the generated heat as well as by the volume alterations caused by the phase transformations lead to an unstable stress field. This stress field is superposed onto the two previous ones induced by the pure mechanical and the pure thermal effects, which makes the prediction very complex in real cutting processes.

3.2.2 Modelling of Residual Stresses

Residual stresses in machined surfaces have been investigated since the early 1950s, leading to handbook data (experimental approach). More recently, finite element methods of machining have been used to predict residual stresses from computed stress and temperature distributions. However, such methods are highly time consuming and very costly. As a consequence, new approaches combining experimental, analytical and numerical models appeared recently in order to enable a rapid prediction of the residual stresses within a few minutes, making this approach usable for industrial applications.

The large majority of these researches are interested in predicting the residual stress state after orthogonal turning (or grinding), which is a 2D problem far from realistic cutting processes (3D turning, milling, drilling, *etc*.). The main limitation to moving towards complex cutting processes is central processing unit (CPU) time. Only few investigations dealt with 3D turning operation but with many more assumptions and uncertainties in order to limit the CPU time [37, 38]. Moreover such models do not consider microstructural modifications, which limit their applications. From this point of view, the cutting scientific community is behind the welding scientific community which has investigated the coupling of metallurgical–mechanical–thermal effects in 3D configurations for a long time [39, 40]. This section aims to provide some trends and references in residual stresses modelling in orthogonal cutting without considering metallurgical changes.

3.2.2.1 Numerical Modelling

Numerical models necessitate the application of standard finite element codes such as SYSWELD, ABAQUS, DEFORM, *etc*. In such approaches, two major types of parameters are strategic (Figure 3.12):

- The input data: mechanical properties of the workmaterial, thermal properties of the workmaterial and of the cutting tool, friction model at the tool–work material interface, *etc*.
- The numerical model:
  - Lagrangian, Eulerian or ALE techniques
  - Adaptative remeshing or none
  - Implicit or explicit formulation
  - Element type and size

The cutting tool geometry is provided by the tool manufacturer (rake and clearance angles, cutting edge radius, chip breaker geometry). Most of the time, authors consider a plane-strain configuration since they consider that the depth of cut is much larger than the feed.

The Lagrangian technique consists of tracking a discrete material point [41]. A predetermined line of separation at the tool tip is usually present, propagating a fictitious crack ahead of the tool in order to avoid severe mesh distortions (Figure 3.13). In this case, a failure criterion is required. The criterion is either based on a distance between the tool tip and the node, or based on a parameter depending on the stress state, on the strain rate and on the temperature at a certain distance ahead of the tool tip. In both cases, the separation occurs when a critical value is reached [42, 43]. However only sharp cutting tools can be modelled. Other kinds of Lagrangian techniques prefer the use of adaptive remeshing techniques to bypass the problem, which enables the modelling of blunt tools [44–46] (Figure 3.14). Of course, the CPU time becomes very high since a fine mesh is required around the cutting edge radius.

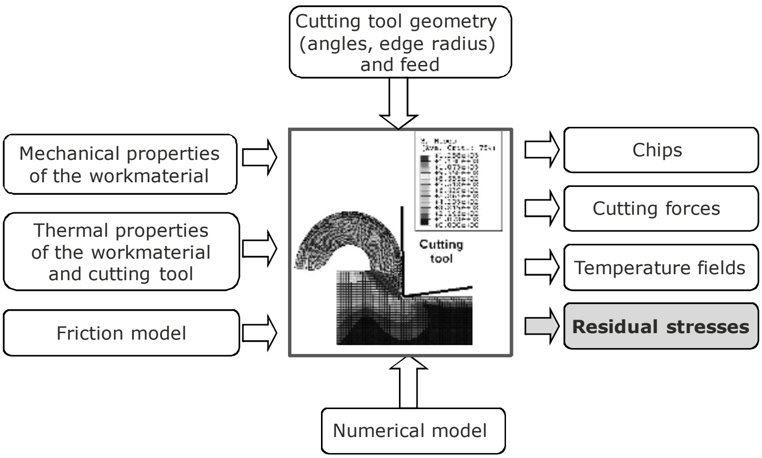

Figure 3.12. Data involved in the numerical modelling of residual stresses

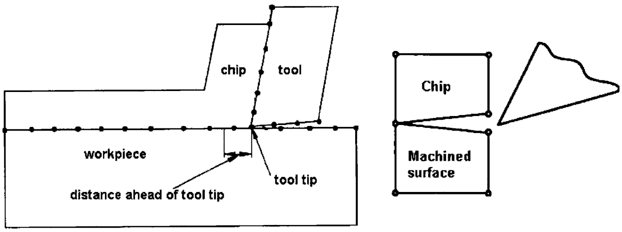

Figure 3.13. Principle of the Lagrangian technique applied to metal cutting modelling

Eulerian techniques consist of tracking volumes and do not induce problems of mesh distortion or require failure criterion [47, 48]. However the determination of free surfaces is critical, which necessitates some assumptions about the chip geometry (no segmented chips, *etc*.). Finally, the avoidance of elastic behaviour does not enable the estimation of residual stresses.

The arbitrary Lagrangian–Eulerian (ALE) technique is a relatively new modelling technique that represents a combination of the Lagrangian and Eulerian techniques without their drawbacks [49]. Figure 3.15 illustrates an application of this approach. Regions A, C and D were modelled as Lagrangian regions with adaptive meshing. So free surfaces can be modelled properly and boundary conditions can be applied in a simple way. Consequently, automatic chip formation takes place. Region B was modelled as an Eulerian region, where the mesh is fixed in space and the material flows through it. This solves the problems encountered around the tool tip.

In metal cutting simulations, authors usually apply explicit integration methods; although some works are available with implicit methods [44, 50]. In explicit integration, a system of decoupled differential equations is solved on an element-by-element basis, in which only the element stiffness matrix is formulated and saved without the need for the global stiffness matrix. On the other hand, the global stiffness matrix has to be formulated and saved in implicit integration, and the whole system of differential equations has to be solved simultaneously. Therefore, explicit methods are computationally more efficient, especially when non-linearity

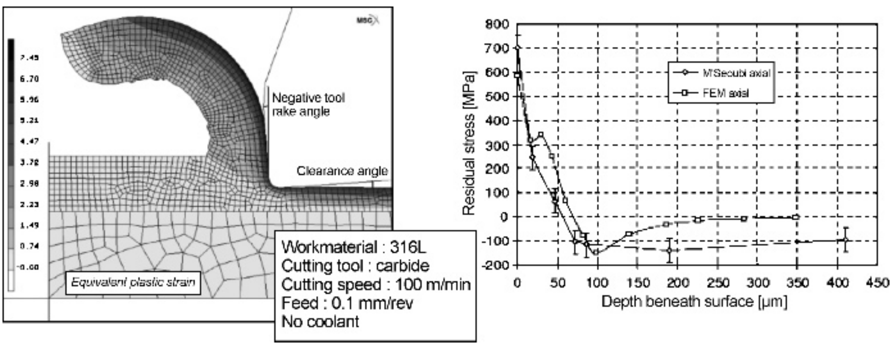

Figure 3.14. Example of Lagrangian model simulating the residual stresses of a 316L steel [46]

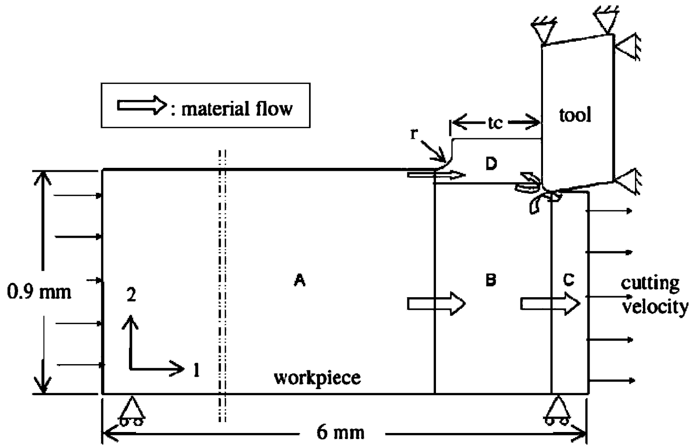

Figure 3.15. Principle of the ALE technique applied to metal cutting numerical modelling since [49]

is encountered. This becomes more evident in thermally coupled analysis, as in metal cutting, because structural and thermal variables are solved simultaneously. On the other hand, explicit integration is conditionally stable because the critical time step depends on the minimum element size and the speed of wave propagation, while implicit integration is unconditionally stable [51].

Concerning the input data of numerical models, the identification of the constitutive equations for the work material (flow stress model and damage model) remains an issue, since it requires the determination of material properties at high strain rates, large strains, high temperatures and high heating rates. The main problem originates from the strain rate achievable in standard mechanical tests (for example, Hopkinson's bar), which are about 100 times too slow compared to classical strain rates in metal cutting ~10^5–10^6 s^{-1}. A common practice consists of using the Johnsson–Cook model, including deformation hardening, thermal softening and rate sensitivity. Another major problem originates from the identification of the coefficients independently from each other, *i.e.*, the strain rate effect is identified at low temperature, the temperature effect is identified under low strain rates, *etc*. As a consequence, there is no way to validate that such models remain meaningful under the combination of high strain rates and high temperatures. Some authors have underlined the sensitivity of Johnsson–Cook parameters on the residual stresses predicted to prove the necessity of improvement of the identification methodology and of the constitutive models [44].

Friction is also one of the most critical parameter in metal cutting. Indeed, it is the most sensitive parameter for the determination of residual stresses, since a small modification of its value induces large modifications of the residual stress field [43, 52]. A lot of authors assumed that the Coulomb friction model is valid, with a constant coefficient irrespective of the pressure and of the temperature. Newly developed tribometres combined with numerical models enable the identification of more realistic friction models [53].

Due to the transient thermal and dynamic behaviour of the model, it is necessary to relax thermally and mechanically the workpiece after the cutting process in order to quantify residual stresses.

All these models provide relevant information in the range of application for which they have been developed for. Usually, scientific papers present results for a limited number of cutting conditions, without showing the capacity of the model to extrapolate results for other applications. An example is provided in Figure 3.14. However the CPU time required to obtain an acceptably accurate result is around 1 or 2 weeks even with a powerful computer, which does not currently enable its industrial application. However such models are useful for researchers, since the residual stress prediction can be made for several configurations, which facilitates the investigation of the sensitivity of these parameters. This also enables the development of cutting operations based on residual stress criterion by modifying:

- Cutting conditions: cutting speed, coolant, *etc*.
- Cutting tool geometry: edge radius, angles, *etc*.
- Cutting tool material: coatings, substrate, *etc*.

3.2.2.2 Analytical Modelling

The objective of analytical models is to predict residual stresses based on equations coming from mechanical and thermal properties of work materials. Such models are very efficient in terms of speed compared to experimental or numerical approaches. Moreover such models enable the effects of each parameter on the system to be understood in detail, which is necessary for any process optimization.

Pure analytical models are almost nonexistent since they are unable to model dynamic movement. Indeed, the cutting boundary changes continuously during machining. So modelling a turning process from the beginning to a steady state becomes complex. As a consequence, most authors apply the finite element technique to solve this problem. Compared to the previous approach, the numerical calculation is only used to facilitate and accelerate the resolution of the mechanical and thermal equations for each step. It especially enables to record the history of thermo-mechanical loading and unloading. From a practical point a view, authors have to perform three kinds of operations (Figure 3.16):

1. Quantifying the thermo-mechanical loadings supported by the machined surface
2. Moving the thermo-mechanical loadings with the velocity corresponding to the cutting speed
3. Removing the loadings and waiting for the relaxation of the thermal and mechanical field before quantifying the residual stress fields.

Based on this statement, each author has a different way to quantity the thermo-mechanical loadings supported by the machined surface. Some authors consider only thermal loadings and neglect mechanical effects [54]. Other authors prefer processing the thermo-mechanical loadings in two steps:

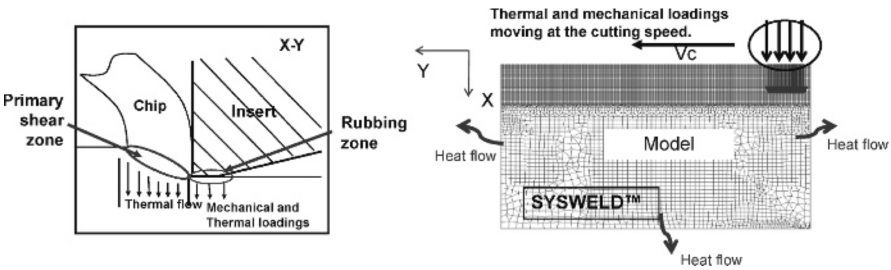

Figure 3.16. Principle of moving sources [52]

1. A first calculation aims to model the heat transfer between tool, chip and workpiece. Heat sources coming from the shear energy in the primary shear zone and from the friction energy produced at the tool rake face–chip contact zone. The heat generated from the friction at the flank face–workpiece interface is not considered by some authors [55], whereas other authors consider it to be of primary importance [52, 56]. The quantification of each parameter is always problematic, considering: the heat partition coefficient, heat exchange coefficient with the environment, amount of plastic deformation energy converted into heat, repartition of the heat flux density along the contact surface, availability of a relevant friction model (see previous section), influence of the coating etc. Among the articles using this approach, each author has their own choice depending on the data available in the literature. However, based on this thermal analysis, the temperature distribution within the workpiece is calculated. Temperature gradient leads to a non-homogeneous mechanical stress field.
2. A mechanical load is combined with the preliminary stress. At this step, two strategies exist. The first strategy consists of neglecting coupling effects [56], whereas the second strategy consists in taking into account this thermo-mechanical coupling [52]. Such an approach induces the absence of coupling between mechanical and thermal phenomena. However, the quantification of each parameter remains a problem: repartition of the pressure over the contact surface, area of contact surface, isotropic or kinematic hardening, *etc*. Depending on the author, various solutions exist. Some authors use pure theoretical models [55], whereas others prefer using experimental data obtained basic orthogonal cutting tests (cutting and feed force, flank face contact area, chip thickness, *etc*.) [52, 56].

Such analytical models enable one to obtain interesting results in terms of precision (example in Figure 3.17) and CPU time (some minutes according to [52]). Models combining analytical equations fitted by experimental results can be considered as a realistic way to model residual stresses before the development of efficient and rapid numerical models.

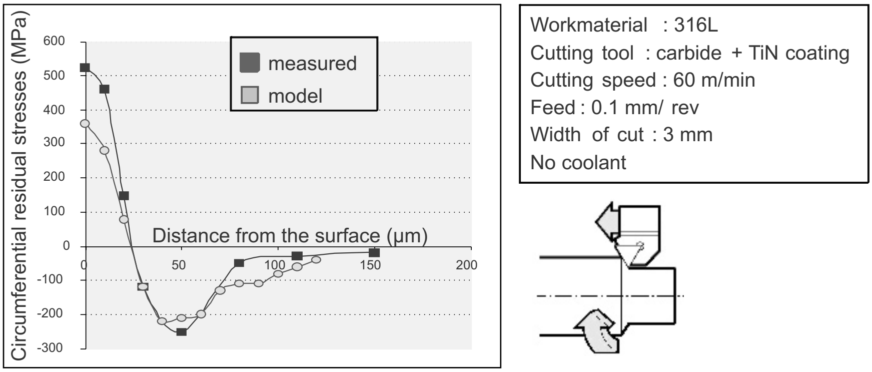

Figure 3.17. Example of results obtained by analytical models [52]

All these models (analytical and numerical) contribute to a better understanding of the phenomena leading to residual stresses. They also enable decision regarding the cutting tool design and the selection of proper cutting conditions to be taken. However, for the time being, all these models have been developed for one specific application: one work material, one kind of cutting tool material, one geometry, *etc*. and their validation is always restricted to few cases because of the cost for each residual stress measurement. As a consequence, there is still no software available on the market that is able to predict residual stress fields for a large range of applications (various work materials, various cutting tools, various cutting conditions, application of lubrication, *etc*.). The great improvement made during the last 10 years leads us to think that such software could appear in the next few years if some leading companies apply pressure and provide financial support to research laboratories in order to determine much more accurately the input data necessary for their models and if the CPU time continues to decrease in order to obtain accurate results within a reasonable time to enable industrial optimization. In the mean time, the experimental approach will probably remain the reference.

3.2.3 Experimental Approach

3.2.3.1 Introduction

The most widely used approach to characterize surface residual stresses induced by machining processes remains the experimental approach. It consists of characterizing the residual stress state and the microstructure before and after the machining operation. The X-ray diffraction technique and the micrograph analysis are the reference for such investigations. The experimental approach is very efficient to provide results, but it requires several days of characterization. Moreover, the cost of such equipment and the complexity of their application necessitates competent engineers, which leads to very high cost (several hundreds to thousands of US$ for each piece, depending on the number of directions investigated, the precision required and the number of points on the profiles).

However such results exhibit large deviations since a large number of cutting parameters have a strong influence on the residual stress profile. Parameters such as cutting speed, feed, *etc*. are very commonly known, but information about parameters such as cutting edge preparation, lubrication (nature, application) and wear of cutting tools is not always reliable and can vary significantly. Such parameters are well known to have a strong influence on the residual stress profile since they modify entirely the thermo-mechanical load supported by the surface [12, 13]. Most of the time, such detailed information is not clearly expressed, or controlled. As a consequence, it is necessary to carry out several characterizations for each case study in order to find the lower and upper bounds of the results, including standard industrial deviations. Based on this range of results, it is possible to take decisions regarding the capability of a process. This necessitates a lot of time and money in order to obtain reliable information. As a consequence, few companies are willing to perform such investigations, except the aircraft industry, the nuclear industry and the automotive industry for some strategic surfaces concerning safety parts. Usually, companies prefer to select their manufacturing conditions based on common criteria: cost, time, wear, accuracy, *etc*. and subcontract the characterization in order to validate (or not) the surface integrity. The main problem with this approach is that the probability of satisfying the specifications is rather poor since there are no basic reliable models available on the market that are able to predict the results (see the previous sections). As a consequence, companies are ill equipped to take a decision regarding the modification of one parameter among all the possible parameters. When the residual stresses have to be compressive in the external layer, the least hazardous solution consists of adding a super-finishing processes such as honing, belt finishing or roller burnishing. However such solutions are very expensive and delay the time to market of the product.

When companies decide to perform residual stresses measurements, some prefer measuring residual stresses on the external layer only. This practice is risky since the external residual stress level is very sensitive. A small variation of the process parameters can lead to large variations in its value. On the contrary, the shape of the residual stress profile is much more stable, so it is highly recommended to analyze residual stress profiles instead of single external values.

From the 1950s to the 1990s, the number of investigations was rather limited since the characterization methods were rather rare, expensive and difficult to manage. The development and diffusion of the X-ray diffraction technique have enabled a strong acceleration of these investigations in laboratories and industry. Since this time, the scientific literature has provided a large number of papers dealing with a wide range of machining techniques. It is almost impossible to provide a comprehensive description of all of these investigations. It is only possible to give an idea of the results provided for some key applications, which have driven large improvements in the basement knowledge.

The following sections will be devoted to the presentation of some typical cutting processes with common parameter (not extreme) values and the corresponding induced residual stress states.

3.2.3.2 Grinding

Among the machining technologies for which data dealing with residual stresses is available in the literature grinding is probably the most investigated process, for several reasons. Firstly it is a finishing technology and, as a consequence, is an important contributor to the fatigue and wear resistance of the surface. Second, this is a very sensitive technology involving a high concentration of energy dissipated through narrow surfaces, which may induce easily thermal damages (white layers, oxidation, burn, *etc*.). Moreover grinding is applied in almost all strategic parts of typical mechanisms: motor engines (crankshaft, camshaft, valves, *etc*.), gear boxes (gears, shaft, *etc*.), turbine engines (blades, rotors, *etc*.), and so on. As a consequence of the high potential risk of this technology, combined with the high stakes in such leading industries, a lot of investigations have been undertaken in order to qualify and model surface integrity in grinding.

Before presenting some typical residual stress profiles generated in grinding, it should be noted that there are a large variety of parameters:

- Work material: composition, microstructure
- Grinding wheel: material – c-BN, alumina, SiC- and structure
- Lubrication: composition, application (pressure, nozzles, *etc*.)
- Dressing conditions
- Grinding conditions
- Wear of the grinding wheel

For each configuration, the physical phenomena are very different, which leads to a large variety of residual stress profiles (tensile or compressive states in the external layer, with or without phase transformations). Surface integrity in grinding depends on the thermo-mechanical loadings supported by the work material and on its metallurgical properties. At the grain scale, different phenomena occur: microchip formation, ploughing, rubbing, *etc*. Grinding operations necessitate powerful machines. A large amount of the energy consumed is dissipated into heat because of the predominance of ploughing and rubbing phenomena (plastic deformation), which lead to a very poor energy efficiency ratio. So, grinding is a machining process that involves high concentrations of heat fluxes at the interface, combined with large contact areas, in comparison to other techniques (turning, *etc*.). The objective of the manufacturer is to dissipate this energy into the grinding fluid instead of into the work material (where it can cause surface integrity damage) or into the grinding wheel (where it can cause excessive wear and dimension variations). However, the complexity of the grinding wheel structure and the difficulty that the grinding fluid has in reaching the contact area due to the high tangential speed (from 30 m/s in conventional grinding to 200 m/s in high-speed grinding) lead to large deviations in the results, which classify this technology among unstable processes. A small difference in the parameters listed above can change the results dramatically.

When no phase transformation occurs, tensile stresses are always observed in the external layer because of the predominance of plastic deformation induced by the thermal expansion of the work material (Figure 3.18). However, an increase of

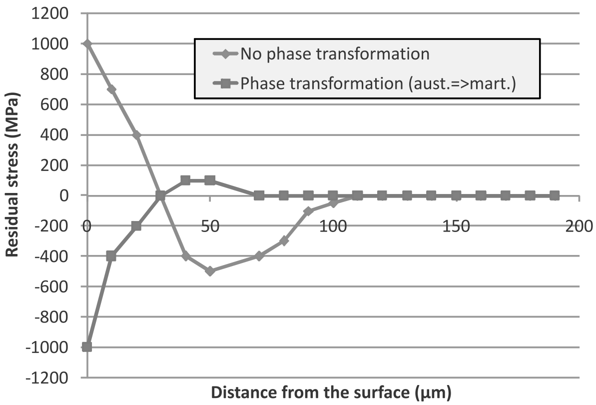

Figure 3.18. Typical residual stress profiles obtained after grinding

the grinding speed leads to high temperatures. When a defined temperature is reached, phase transformation may occur (for example, martensite ⇔ austenite). The rapid cooling of the surface leads to quenching and variation of volumes which may induce compressive residual stresses (austenite to martensite) or tensile stresses (martensite to austenite) (Figure 3.19).

A large number of authors have investigated the influence of grinding parameters on the surface integrity and it is almost impossible to mention them all [34–35, 42, 57–66, 30–31]. Among these investigations, authors have dedicated a large number of articles to the characterization of high-speed grinding involving c-BN wheels, since this enables the improvement of surface integrity (residual stresses, surface texture, wear rate, *etc*.) combined with a large gain in productivity.

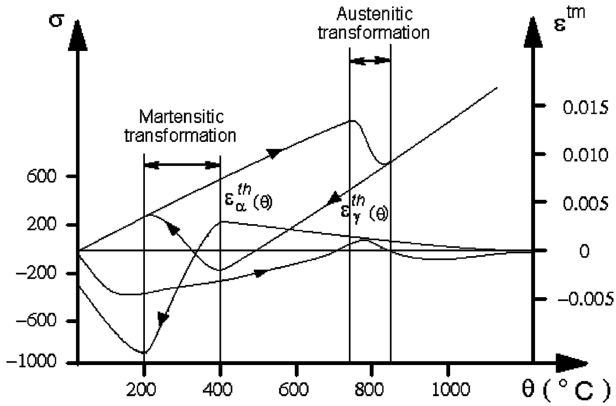

Figure 3.19. Mechanisms of residual stress generation associated with phase transformations [34, 35]

3.2.3.3 Turning

The second most widely investigated machining technology is probably turning. Since [67], various papers were published intermittently until the end of the 1990s. Companies manufacturing turbine engines associated with academic laboratories were the main contributors to this literature. Due to the difficulties in obtaining such data and the cost, only part of these investigations has been published. Moreover, most of the investigations were concerned with high-strength steels (*e.g.*, 39NiCrMo16), stainless steels (*e.g.*, 316L) and titanium alloys (*e.g.*, TA6V). Since the 1990s, the appearance of c-BN tools has completely changed the manufacturing processes in the automotive, aircraft and bearing industries. The possibility of replacing grinding operations by dry hard turning operations has brought about new opportunities for productivity improvements. In this period, the question was: is the surface integrity induced by hard turning appropriate for the fatigue/wear resistance of the machined surface. As a consequence, since this period, a large number of papers dealing with surface integrity in hard turning have appeared in scientific journals.

Turning of Austenitic Stainless Steels AISI316L with Carbide Tools [49, 68, 52]
Residual stress profiles induced by turning all have a similar shape (Figure 3.20). Tensile stresses are present on the external surface, followed by a large compressive peak in the sublayer. Among the strategic parameters, small nose radii and low cutting speeds are favourable to decrease the stress level and the affected layer thickness. Feed has a strong influence on the affected layer thickness.

Turning of Titanium Alloys (TA6V) in their α+β Structure with Coated Carbide Tools [23, 69]
External residual stresses are compressive. The affected layer can increase from 100 to 400 μm with increasing cutting speed. The fatigue resistance in four-point bending tests seems to be much more highly correlated with surface texture than to the residual stress state.

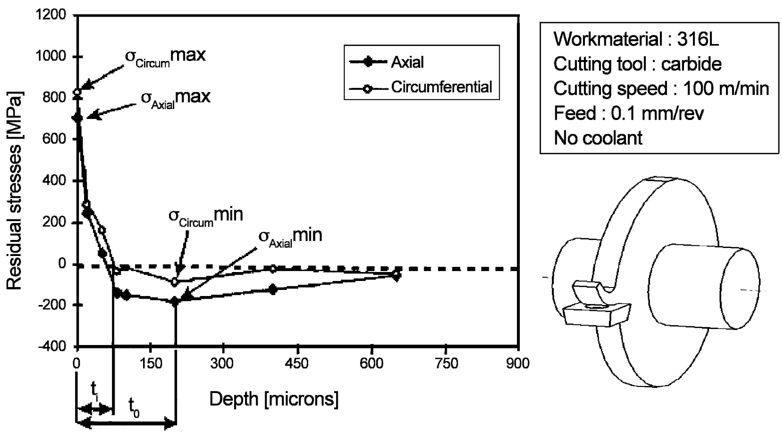

Figure 3.20. Example of experimental measurements obtained after turning of 316L [68]

Turning of Inconel718 in Their Hardened State with Mixed Ceramic Tools or c-BN Tools [70–71]
Ceramic tools induce larger tensile residual stresses compared to c-BN cutting tools when they are used in their own functioning domains (450 m/min for ceramic and 250 m/min for c-BN). With new tools, c-BN cutting tools generate compressive residual stresses, whereas wear changes it to tension. The residual stress is sensitive to cutting speeds. At low cutting speeds (~10–200 m/min) compressive residual stresses are generated, whereas tensile stresses are generated at high cutting speeds (~350–810 m/min). Round inserts and the application of coolant are much favourable to compressive stresses.

Turning of Inconel718 in Their Hardened State with Coated Carbide Tools [72]
As cutting speed increases the surface residual tensile stress drops while an increase in feed rate results in a slight increase in both the surface tensile stress and the depth of the compressive stress layer. The largest influence on the surface integrity generated is caused by tool wear.

Turning of Annealed Steels (C45, AISI1018) in Their Ferrito-Perlitic State with Carbide Tools [73–76]
Tensile stresses are obtained in the external layer, followed by a thick compressive layer. The parameters with the greatest influence seem to be the cutting speed and feed rate. An increase of the cutting speed seems to move residual stresses toward tension and to decrease the thickness of the affected layer. An increase of feed or wear makes the residual stresses more tensile, but increases the thickness of the affected layer.

Turning of Medium Carbon Steels (42CrMo4) in Their Bainito-Martensitic State with Coated Carbide Tools [77]
The most important parameters seem to be cutting speed, feed and wear. An increase of feed and wear seems to make the residual stresses more tensile, whereas a high cutting speed seems to make them more compressive. The application of lubrication seems to worsen residual stresses and increase the thickness of the affected layers. In contrast, the influence of the depth of cut does not seem to be significant.

Turning of High Resistant Steels (30NiCrMo16, 39NiCrMo16) in Their Martensitic State with Coated Carbide Tools [23, 78]
Tensile stresses are present in the circumferential and axial directions on the external surface, followed by a compressive layer below. The affected layer is lower than 400 μm thick. The effect of cutting parameters is controversial: [78] indicates that feed rate and nose radius are the most influential parameters, and that cutting speed has little influence; in contrast, [23] indicates that the external residual stress state decreases with increasing cutting speed and decreasing nose radius and feed rate. Additionally, external residual stresses seem to decrease with increasing depth of cut and seem to be minimum for cutting tools having a leading angle K_r of about 90°. The fatigue resistance in four-point bending tests seems to be corre-

lated with the residual stress state and not with the surface texture. In this context, the best fatigue performance for cutting applications is obtained using cutting tools having a small nose radius, a leading angle around 90° and a high cutting speed.

3.2.3.4 Hard Turning

The hard turning technique has been considered independently from the previous turning application, since this technique is in direct competition with grinding (work materials HRc > 55). Moreover, cutting tools for hard turning have a totally different substrate (c-BN instead of carbide) and their geometry is totally different (strong negative rake angles) from turning operations of steels with lower hardness. As discussed previously, this technique has been intensively investigated since the 1990s due to its high productivity.

The influence of some cutting parameters on residual stresses of a case carburized steel with hardness in the range HRc 58–62 has been investigated [20], showing that external residual stresses after hard turning are not significantly affected by depth of cut and feed rate. These observations and highlights have been confirmed [12], and it was reported that cutting speed and tool wear were the most influential parameters, leading to tensile stresses and microstructure modifications in the external layer. The influence of tool wear has also been confirmed by [6, 21–22, 62, 79–80]. There exists a tendency for the thrust force to increase gradually with the increase of the tool wear [80]. Moreover there is an increase of the contact area at the tool–workpiece interface. As a consequence, tool wear leads to higher thermal process energy related to the increase in friction, leading to a shift of the residual stresses towards tension in the external layer.

It has been reported that feed greatly influences residual stresses in the sublayer [81]. A high feed rate leads to higher compressive stresses into the material and moves the compressive peak deeper.

In parallel, some authors have investigated the influence of the geometry of cutting tools [20, 80, 82–84]. Thiele and Melkote [82] investigated the subsurface residual stresses in longitudinal turning of through hardened AISI52100 bearing steel with different tool edge preparations while keeping the cutting parameters fixed. By using X-ray measurements, they found that hone edge preparation produces more compressive residual stresses than the chamfer edge geometry after machining a workpiece hardened to HRc 57. Additionally, they showed that the penetration depth is more important with hone edges. This trend is expected for bearings in order to ensure satisfactory rolling contact fatigue, due to the fact that the maximal shear stress is not at the surface but some micrometres below.

Other investigations [20, 85] indicated that the size of the primary shear zone seemed to be of secondary importance, while the size of the plastic zone near the tool edge seemed to play a major role. They observed that the hone edge and the double chamfer geometries offered the greater subsurface penetration, and produced larger values of maximum compressive stress, compared to a sharp edge.

Liu *et al.* [80] explained the influence of the honed edge by the fact that a small depth of cut and low feed rates are chosen in hard turning. So, the undeformed chip thickness has the same order of magnitude as the radius of the cutting edge or the size of the edge chamfer. Consequently, the chips are formed along the nose of the tool in the region of the edge chamfer or the cutting-edge radius. Therefore, the cutting-edge geometry contributes to larger plastic deformation in the primary shear zone and around the edge, which is beneficial for compressive residual stresses.

Dahlman *et al.* [81] investigated the effect of the inclination angle of the chamfer during the machining of AISI52100 steels and revealed that a large negative angle provides greater compressive stresses as well as a deeper affected zone below the surface. With larger negative rake angles, the position of maximum stress is moved further into the material.

Other studies [86, 80] investigated the influence of the insert nose radius on the residual stresses induced by hard turning. They show that inserts with a small radii lead to much more compressive stresses in the external layer, compared to rounder insert. Liu *et al.* [80] explained this trend by a pure geometrical effect: a smaller contact area for an almost equivalent force increases the pressure at the tool–workpiece interface, leading to larger plastic deformation in the machined surface.

Rech and Claudin [84] revealed that a wiper nose geometry has a beneficial effect on residual stresses toward compression. Additionally cutting tools with a TiN coating and a low c-BN content are much more favourable for a compressive state.

Finally the service performance of hard turned surfaces compared to ground surfaces has been investigated [87, 20]. Hard turning can induce surface integrity, when machined in selected conditions, which can be without thermal damage and superior to grinding. The most exciting new opportunity for hard turning is its capability to produce compressive residual stress, in a wide range with sufficient magnitude and depth, which is not possible with conventional abrasive-based processes. It enables to reach desired pre-stresses. Experimental data has been reported to show that the fatigue life of hard turned surfaces is better than that of ground surfaces. However, the best turning parameters can result in as much as 47 times better fatigue life than that from the worst turning parameters with the same surface finish. Therefore, the method of selecting hard turning parameters is extremely important for obtaining the incredible benefit of hard turning in terms of fatigue life. However, for one set of cutting parameters and cutting tool, the fatigue resistance can be significantly worsened by excessive tool wear, as shown by [18].

3.2.3.5 Milling

In contrast to the two previous manufacturing techniques, milling has been poorly investigated. Indeed, surfaces machined with these processes are not critical parts for the fatigue resistance. The exception is parts involved in aircraft structures, mostly made of aluminium alloys. As shown by [18], milling operations of aircraft structures with small sections significantly affect distortions. The wide majority of investigations dealing with peripheral or face milling were concerned with aluminium from the 2000 or 7000 families.

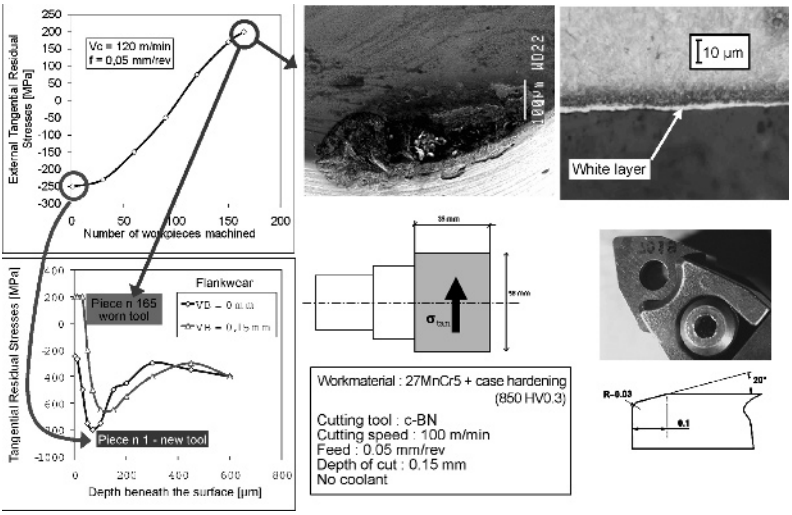

Figure 3.21. Example of residual stress profiles in hard turning [12]

Another field of research on surface integrity in milling is machining with end mills and ball nose mills. Such investigations were promoted by the development of the high-speed cutting (HSC) technology in two main areas: the production of dies and moulds, and the production of turbine blades made of super alloys (titanium, Inconel718, *etc*.), because such parts are very long and expensive to produce. Moreover they are submitted to intensive thermo-mechanical fatigue cycles. The expectation of industry was to finish parts directly from milling in order to avoid super-finishing processes (honing, belt finishing, *etc*.), which are well known as being favourable for surface integrity improvement.

Peripheral and Face Milling of Aluminium Alloys (7075 T7351, 2024 T351) [18, 23, 88, 89]

Residual stresses are affected by the cutting speed and the working mode. In particular, it is recommended to machine at low cutting speed under up-milling trajectories. Depth of cut is a secondary important parameter, for which a low value seems to be more favourable. The effect of coolant can be neglected since its effect is only important for low cutting speed, which is rather unusual in the aircraft industry. The effect of feed is not so clear. Indeed some authors [23, 89] recommend a low value, whereas others [18, 90] recommend high values in order to induce compressive stresses and thick affected layers. Finally a cutting tool with a large nose radius is recommended.

It should be noted that the residual stress state is very different in the direction parallel to the feed and in the perpendicular direction (an opposite sign may occur). The thickness of the affected layer is usually less than 0.2 mm. The fatigue resistance of aluminium parts in four-point bending tests seems to be more closely correlated to their residual stress state than to their surface texture.

Face Milling of Annealed Steels (C35, C45, C60, 42CrMo4) [91–94]
Compressive residual stresses are obtained much more easily if an up-milling strategy is selected. Cutting speed, feed and wear should be kept as low as possible in order to improve the surface integrity. However it appears that milling induces different stresses in the direction parallel to the feed and in the perpendicular direction (opposite sign may occur). Indeed, [93–94] expect tensile stresses in the direction parallel to the feed and compressive stresses in the opposite direction, whereas [91–92] expect compressive stresses. However the thickness of the affected layer is usually less than 0.15 mm.

Face Milling of Treated Steels (C35, C45, C60) [94]
Residual stresses are in traction at the surface and tend to become compressive inside the material.

Ball Nose Milling of Tool Steels (H13) or Inconel718 [95, 96]
High compressive stresses can be obtained with low cutting speeds, low feeds and low orientation angle of the tool (tool perpendicular to the surface). The trajectory is also a very sensitive parameter: a horizontal upwards cutter orientation (measured parallel to the feed direction) is critical to obtain compressive instead of tensile stresses when machining with a horizontal upwards strategy.

3.2.3.6 Super-finishing

From the previous sections, it is not surprising to announce that super-finishing processes have also been investigated since they are applied on critical surfaces submitted to fatigue and wear. The main difficulty with super-finishing techniques comes from their variety. A large number of super-finishing are available (honing, belt finishing, belt grinding, lapping, polishing, electro-chemical polishing, burnishing, roller burnishing, *etc.*). Moreover, the application of each super-finishing technique necessitates a lot of adaptation, which induces differences in surface integrity (surface texture and residual stresses). For example, the application of belt finishing to cylindrical parts such as bearings [97] is totally different from its application to crankshafts [98]. In the first case, the material removal is caused by the axial oscillation of a belt with small abrasive grains, whereas in the second case it is caused by the rotation of the workpiece but with larger grains. Additionally, the comparison between the surface integrity obtained after the belt finishing of crankshafts made of bainitic steel (*e.g.*, 35MnV7) or spheroid cast iron is very difficult. As a consequence, each scientific paper dealing with the surface integrity of super-finishing processes is usually difficult to exploit for other investigations, which does not facilitate the understanding of the fundamental mechanisms.

Belt Finishing/Belt Grinding on Hardened Steels [97, 99]
The belt finishing technique applied to hardened steels or on super alloys leads to compressive residual stresses in a thin layer ~10 μm in both the circumferential and axial directions. Such a technique never leads to thermally affected layers if it is used with plain oil lubrication.

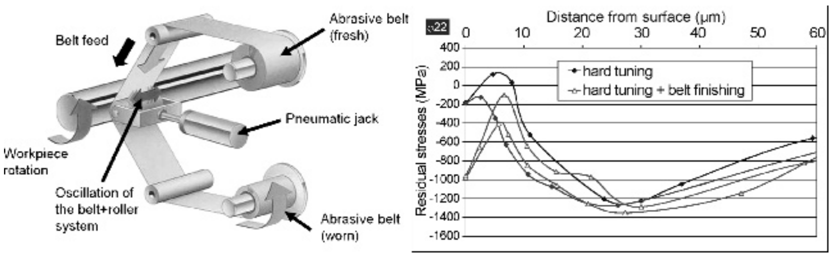

Figure 3.22. Residual stresses induced by belt finishing on a AISI52100 hardened steel

Lapping on a Hardened Steel [100]

Lapping induces strong compressive residual stresses in the surface and leads to great improvements in the fatigue strength of a martensitic stainless steel during plane bending fatigue tests, compared to conventional grinding operation.

Honing on Hardened Steel and Hastelloy X [20, 97, 24]

The honing technique shifts the external residual stress profile towards compression. Rotation bending fatigue tests and pulsating push–pull fatigue tests have shown a great improvement of the resistance compared to a shot peening operation. This improvement was even better in an aggressive atmosphere (water + sodium chloride) than in air, which proves the improvement of the resistance against stress corrosion.

Burnishing/Roller Burnishing of Hardened Steels [14, 27, 101, 102]

In roller burnishing operation, a hydrostatically borne ceramic ball rolls over the component surface under high pressure. The roughness peaks are flattened and the quality of the workpiece surface is improved. Roller burnishing delay the appearance of cracks in grooves. It has been shown that this process is able to generate deep compressive stresses in both the axial and circumferential directions. Hard roller burnishing does not generate any white layers. The affected layer is very thick (~5 mm).

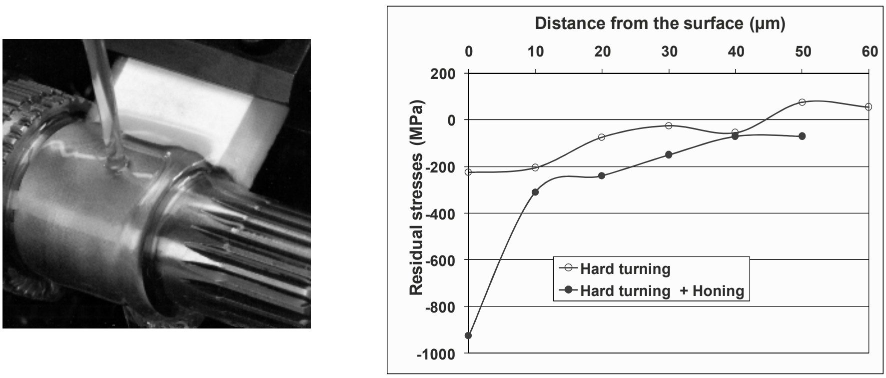

Figure 3.23. Influence of the residual stresses induced by honing on a AISI52100 hardened steel

Note that the residual stresses in reamed surfaces have some similarities with burnished surfaces. Reamed surface are compressive in nature. This is because of the rubbing and plastic deformation of the material caused by the sizing section of the reamer.

3.2.3.7 Hole Manufacturing

In contrast to the previous processes, machining processes such as drilling, reaming, *etc*. are poorly investigated. Small holes are usually not considered as critical surfaces in terms of fatigue resistance. Moreover, it is very difficult to investigate the surface texture of holes and almost impossible to investigate the residual stress fields, at least by X-ray diffraction. Problems with surface integrity of holes are rather recent. Indeed, critical surfaces have been intensively investigated and holes have been neglected. As a consequence, great improvements have been made on some surfaces whereas holes have not experienced any benefit. In parallel, the increase of the thermo-mechanical loadings supported by some parts such as crankshafts with the power increase of motor engines, or by some parts from turbine engines, have led to breakages. As a consequence, holes are starting to be the focus of attention of researchers. After the statement about the poor knowledge on surface integrity induced by drilling and reaming, some companies have decided to apply super-finishing processes such as roller burnishing or honing to induce compressive stresses and improve surface texture. This clearly shows how a lack of knowledge leads to abusive production costs.

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