Chapter 1

Introduction

1.1 Surface Integrity and Demands of Manufacturing Industry

Grinding is a commonly used finishing process to produce components of desired shape, size and dimensional accuracy. However, to achieve a high surface integrity, it is necessary to have an in-depth understanding of the interrelationship between grinding conditions, material properties of workpieces and quality of ground components.

1.1.1 Surface Integrity

The importance of surface integrity depends upon its impact on product performance [Shaw (1996)] such as: fracture strength, fatigue strength, corrosion rate, stress corrosion cracking, wear, magnetic properties and dimensional stability. Surface integrity includes all aspects related to the quality of surfaces such as surface finish, metallurgical damage, and residual stresses [Field and Kahles (1964)]. Surface finish is related to the geometry of the produced surface which is usually measured in terms of peak-to-valley roughness on the European Continent and in Japan or in terms of the centreline average in U.K and the U.S.A. The importance of surface finish may arise, for instance, in some applications in which the orientation of the grinding scratches relative to the loading of the surface plays an important role in the fracture strength of the ground surface. For example, a tensile loading stress across the loading direction brings about lower fracture strength compared with that along the loading direction. As the second aspect of surface integrity, metallurgical damage is characterized by change of microstructure, change in surface hardness, and the presence of microcracks in very brittle material or by change in fatigue strength, fracture strength, stress corrosion cracking, or the rate of wear. One cause of the change of surface hardness is due to phase transformation under a critical temperature history. For instance, phase transformation may be formed by austensing and quenching of steel ground components. The third aspect of surface integrity, i.e. residual stresses, is related to fracture strength, fatigue strength, corrosion resistance, wear resistance and dimensional stability, and is coupled with metallurgical characteristics of the workpiece material. Therefore, the development of residual stress in ground components must be understood fully.

1.1.2 The Role of Residual Stresses in Ground Components

Grinding processes impart a residual stress in the surface layer as a result of irreversible workmaterial distortion and property change. In grinding, residual stresses tend to be tensile when more abusive conditions are imposed particularly at elevated grinding temperatures. By using gentle grinding conditions, however, residual stresses may be altered in magnitude and can even become compressive. Based on the nature and the distribution of residual stresses across the subsurface of a ground component, surface integrity may be either improved or reduced to an extent relying on the grinding conditions.

It has long been recognized that failure of engineering components subjected to an aggressive environment may occur under applied stresses well below the strength of the material [Gdoutos (1990)]. For instance, under the action of a residual tensile stress, metals operating in an aggressive media (for example, in sea water) are subjected to intensive corrosion (stress corrosion cracking), which is one of the major causes of material failure [Dickson et al. (1985)]. Moreover, stress corrosion cracking can give rise in engineering material to a microscopic crack front that leads to a macroscopic front. As one of the environmental effects, for instance the action of atomic radiation on the product surface, the contact of steel with free hydrogen atoms results in the diffusion of the latter into the atomic grid of steel which in turn leads to dangerous embrittlement of the surface [Kachanov (1986)]. Based on the theory of surface energy minimization, the existence of microcracks forces the absorption of hydrogen at the internal surface at the tip of microcrack. In this case, a chemical bond would be formed between metallic atoms. As a consequence, the fracture toughness of embrittled materials decreases and the nature of these materials changes drastically.

For thin components such as plates in particular, the most important consequences of residual stresses are the irreversible deformation of the ground surface of workmaterials which in turn leads to geometry distortion due to residual stress relaxation and alteration of the surface dimensional tolerance.

In general, residual stresses in workmaterial compose a prestressed state that should be taken into account while external loads are applied. Therefore, more attention should be paid to subsequent practical applications of the ground product to meet surface integrity and design specifications.

1.2 Causes of Residual Stresses Induced by Grinding

In general, ground components, such as gears, bearings and cams, are subjected to external loads of thermal and mechanical origin and therefore are governed by the developed remaining stresses, named as residual stresses, which need to be within limits to improve the surface integrity. The nature of the residual stresses depends to a great extent on the manufacturing processes required to produce the final product.

To achieve final dimensional accuracy, unwanted material needs to be ground and thus removed. As a final material removal process, a grinding operation involves abrasive grains and workpiece interaction, which results in interforces that lead to different deformation mechanisms such as (1) work material removal characterized by separation of surface layers and formation of chips, (2) ploughing of the ground surface recognized as the generation of grooves and side ridges and (3) surface rubbing. Thus careful selection of grinding wheel characteristics needs to be made and grinding conditions need to be investigated. The details of the interaction forces between the grinding wheel and the workmaterial are reflected by the grinding conditions described by dimensional and non-dimensional parameters such as grinding wheel speed, table speed, depth of cut and thus the apparent inter contact zone between the grinding wheel and workmaterial.

In contrast to other material removal processes, a grinding operation requires more energy to remove the same material volume and thus has a higher specific energy. This indeed results in high generation of heat energy. The level of heat generated depends not only on the interaction forces within the grinding zone but also on the plastic deformation mechanism associated with the material removal process, the table speed and the grinding wheel speed. Consequently, the workmaterial temperature rises to a level governed by the thermal properties of the workmaterial and the grinding conditions. As the workpiece moves with table speed, the grinding temperature starts to decrease due to the cooling effect and thermal energy diffusion into the workmaterial. As a result, the workmaterial experiences complex thermal strains and stresses the level of which may result in critical effective stresses above which the workmaterial may undergo plastic deformation.

With a critical grinding temperature history, phase transformation may be initiated. To be more specific, phase transformation in steel may take place if the workmaterial is austenised and cooled very rapidly. For a given steel alloy, the austensing temperature and the critical cooling rate associated with phase change are mainly workmaterial composition dependent. Phase transformation is characterized by volume growth and hardness increase the mechanisms of which are related to workmaterial composition and the cooling rate of the grinding temperature history. The surface volume growth may result in compressive residual stresses while the hardness increase leads to higher levels of residual stresses in grinding.

As the austenising temperature is much higher than that required to yield thermal plastic deformation, phase transformation is usually associated with thermal deformation. The mechanical residual stresses are dominant in iso-thermal grinding processes or when the grinding temperature is relatively low. Thermal residual stresses, on the other hand, are mainly generated when the specific energy of material removal is very high as for grinding conditions with very high wheel speed and very low depth of cut. The combined effects of the residual stress sources may arise in some grinding conditions characterized by medium depth of cut, high wheel and table speed. It should be noted that the nature of residual stresses depends to a great extent, on the mechanisms of residual stresses and workmaterial properties.

In summary, the key causes of residual stress mechanisms are (1) residual stresses induced under iso-thermal mechanical grinding conditions, (2) residual stresses due the grinding zone heat energy and temperature rise, and (3) residual stresses associated with phase transformation due to critical grinding temperature history.

1.3 Determination of Grinding Residual Stresses

1.3.1 Introduction

Various methods for determining residual stresses have been developed over the last few decades and can be classified as destructive methods, such as the indentation hardness test, semi-destructive methods such as the combined layer removal and the X-ray diffraction measurement, and non-destructive methods such as X-ray and acoustic emission(AE) methods. The destructive methods are easy to implement. However they can only be used to estimate the maximum fatigue load of a ground part. Added to this, the tested element cannot be of further practical use. Non-destructive methods, on the other hand, are more powerful in terms of their accuracy and speed and more economical in the light of production strategies as they produce damage free tested workmaterial. Unfortunately, the limitation of the above methods in surface residual stresses measurement needs to be resolved by improving the available techniques for a more reliable residual stresses determination.

Although the above methods are useful practical tools for residual stress investigation they cannot explore the residual stress mechanisms, therefore they are said to be post-grinding measurement techniques. Hence predictive techniques are required to analyze the mechanical and/or the thermal deformation associated with a grinding process thus providing in advance useful guidelines for controlling and minimization of severe residual stress effect on ground products. This requires the development of appropriate mathematical models which usually rely on computational mechanics. The finite element method (FEM) and the finite difference method are two of the tools well-known for their power in solving many engineering problems.

1.3.2 Experimental Techniques

1.3.2.1 Destructive Methods

The hardness test has been one of the most common methods of surface hardness evaluation since it can provide information on the properties of the test specimen. Agasaryan (1987) estimated the surface residual stresses for ground steel rings by the PMT microhardness meter. The results showed that as surface microhardness increases, the magnitude of the residual tensile stresses reduces and after a definite microhardness value, residual compressive stresses are observed in the surface layer.

As a semi-destructive technique, the curvature method involves progressive removal of material layers accompanied by X-ray measurements to monitor the variation of residual stresses with depth. In addition to this, there are non-destructive curvature methods which relate the springback deformation (thin workmaterial curvature) to the induced residual stresses. This method is usually useful for assessing the depth of residual stresses. Samuel et al. (1989) measured the residual stresses in several ground ceramics using the curvature method. Ramsey, Chandler and Page (1990) determined the depth of residual stresses in TiN coatings of a few microns thick by measuring the bending of coated coupons as the substrate thickness was progressively reduced by careful grinding. Shibahara and Matsuo (1992) investigated the curvature of a 304 stainless steel thin plate in one pass grinding using WA, CBN and diamond wheels, considered the influences of grinding direction(up-cut, down-cut) and concluded that up-cut grinding causes a larger convex curvature and a higher compressive residual stress than that of down-cut grinding. Schwartz (1995) presented a simple semi-destructive technique for residual stress measurement that obviates reliance upon calibration constants and is suitable for measurement parallel to edges or on the outside radii of ground components.

The merits and the disadvantages of different approaches of residual stress measurements can be assessed by comparing the accuracy and reliability achievable. Kim and Smith (1994) measured the residual stresses in prototype welded tendons experimentally using the blind hole drilling (BHD) technique, X-ray diffraction (XRD) technique and Barkhausen Noise (BHN) method, and discussed the effects of joint configuration, weld repair, weld cap grinding, and pre-fatigue test on residual stresses.

Another destructive method for residual stress measurement is implemented by Yen and Lin (1995) where they measured the distribution of residual stresses on the pipe specimen surface of weld by adopting the hole-drilling strain-gauge method and using the incremental drilling technique to estimate the residual stresses on the inner and outer walls of the weld overlay pipe.

It is clear that the destructive method results in components with permanent damage. Therefore it has considerable limitations for use in practice. The layer removal method, however, may be of great importance if accompanied by a more reliable procedure to account for the problem of stress redistribution

1.3.2.2 Non-Destructive Methods

Non-destructive methods are attractive for residual stress measurement since they may result in damage free products thus saving production costs. Some of the techniques used are the X-ray diffraction method and the acoustic emission method (AE). Toenshoff, Siemer and Wobker (1988) measured the surface stresses introduced in silicon nitride by the X-ray diffraction technique and showed that the grinding treatment of ceramic materials reduces compressive surface stresses and that these are decreasing with increasing cutting speed. The combination of the X-ray diffraction method and the acoustic emission technique may enable automated production. Fix et al. (1990) incorporated Barkhausen noise technology into the X-ray diffraction method and detected grinding stresses and burns on ground automotive steel camshafts thereby providing an automated channel inspection system. Gondi, Mattogno, Sili and Foderaro (1993) examined the structural effects of wet and dry grinding on AISI 4340 steel surface by the X-ray diffraction analyses and compared them with the relevant measurements of magnetic Barkhausen noise amplitudes. They emphasized the importance of Barkhausen noise technique in monitoring of zones of material softening and workhardening. Nan et al. (1993) studied the effects of the grinding wheel, the processing parameters and types of carburised steel on residual stresses by the X-ray diffraction method and observed that in comparison with the corundum (GB) wheel, which forms the tensile residual stresses distributing in a wide range from the surface with fairly high magnitude, the cubic borazon (CBN) wheel generally forms compressive residual stresses at the surface with a low level of tensile residual stresses beneath the surface distributing in a narrow region. Shibano, Ukai and Tadano (1994) presented a new measurement method with polychromatic X-rays for residual stress along the depth direction in a subsurface layer. In this method, the surface stress and stress gradient in a subsurface layer is evaluated by using the theoretical equation describing the relationship between diffracted beam peaks of polychromatic X-rays and a strain distribution along the depth direction. Ukai, Shibano and Ishige (1994) presented a new measurement method of three-dimensional stress using polychromatic X-rays and estimated its three-dimensional stress using an exponential approximation curve for strain distribution. Eigenmann and Macherauch (1995) determined the grinding surface residual stress of some engineering ceramics (pure Al_2O_3, Al_2O_3 with 5 vol.% TiC, and tetragonal ZrO_2 stabilized with 3 mol% Y_2O_3.) with the advantage of the use of X-rays from a synchrotron radiation source but using parallel beam optics to avoid the effect of the ground shallow surface. Sakaida et al. (1995) measured the residual stress distribution near the ground surface by the cos psi method of X-ray stress. They found a biaxial state of compressive stresses decreasing exponentially with increasing the distance from the surface. Sasaki and Hirose (1995) described a study on a method of X-ray stress measurement for the non-destructive determination of the gradient of macro- and micro-residual stress components in the surface layer of composite and non-homogenous materials. Mizutani, Yasui and Okamura (1995) carried out an investigation of the relationship between the grinding force ratio and the residual stress of a ground surface to determine the pattern of residual stress of the ground surface. They measured the residual stress of the ground surface by the X-ray diffraction method and found that a sufficiently small force ratio can result in compressive-stress-type distribution induced by the CBN wheel. Novosel, Radovic and Balen (1995) investigated the dependence of microstructure parameters and residual stress in heat treated samples of carbon by using the counting technique and CoK alpha radiation of a diffractometric system.

The power of the X-ray technique for measuring average surface residual stresses is promising. However, the detailed distribution of residual stresses across ground depth is still questionable. More investigation on the calibration of X-ray results is needed to test its reliability.

The acoustic emission technique is widely used for automated testing in manufacturing processes. Theiner, Kern and Conrad (1986) described the state-of-the-art of ferromagnetic techniques for measuring microstructure parameters and residual stresses and discussed the first applications using incremental permeability and magnetic Barkhausen noise. Akbari et al. (1995) analyzed acoustic emission signals during pendulum scratching of alumina by diamond scribe and related the emission of acoustic signals after the disengagement of the diamond scribe from the workpiece to the residual stress due to scratching. Liang, Devereux and Marinescu (1995) discussed the mechanism of workpiece damage such as residual stresses and investigated destructive and non-destructive methods for detecting grinding damage. They showed that the post-grind AE method is a practical and promising method for detection of grinding damage in ceramic workpieces.

The acoustic emission technique is used mainly to detect the presence of residual stresses indirectly by investigation of workpiece damage. Therefore it is still difficult for the full field of residual stresses to be explored by this technique.

There are other indirect methods of residual stresses assessment by measuring their effects on workmaterial strength. Hoshide, Okumura and Inoue (1991) conducted three-point bending tests using specimens of sintered silicon nitride ground in six types of condition, which were prescribed by the combination of the mesh-size of the grinding wheel and the cutting depth. They revealed by the Weibull statistical analysis that the strength was higher and its scatter was less in specimens ground by a grinding wheel with larger abrasive grains. Virkar (1990) presented a simple beam theory based on recorded strain *vs* thickness ground off data measured by using a strain-gauge technique for the determination of residual stress patterns in thin workmaterial sections such as beams and plates.

The accuracy of the three-point-bending test and beam theory in analyzing residual stress is usually low due to the many simplifications used and experimental measurement errors.

1.3.3 Theoretical Prediction

Usually, a technological study of the grinding process results in the development of a model which is valid for a closely limited field with given boundary conditions. Reliable models for predicting residual stresses are of great value in reducing the amount of measurements and experimental tests of residual stresses. In order to get a full understanding of the mechanisms underlying residual stresses, incremental advancing of the grinding wheel from an early stage of grinding wheel-workpiece engagement to a steady state condition is necessary. To meet these requirements, few efforts have been devoted to develop the appropriate models to account for different grinding conditions, workmaterial properties and the boundary conditions, and no reliable and generally accepted model seems to have been developed.

1.3.3.1 Current Status

Mathematical models associated with grinding processes are required to explore and predict the roles of different grinding parameters on residual stress mechanisms. This needs careful theoretical simulation of a given grinding operation in terms of grinding conditions and workmaterial properties by suitable numerical methods such as the finite element method (FEM) and the finite difference method (FDM). However, due to the nature of deformation mechanisms and the workmaterial properties associated with grinding mechanisms, the finite element method is found to be one of the best modelling tools. Therefore most the mathematical models used were based on FEM.

One cause of residual stresses is due to thermal deformation which may include phase transformation. This is usually observed in the quenching process. Okamura and Kawashima (1989) carried out the computations of heat treatment (quenching) of rings using a theory considering the interactions between temperature, phase transformation and stresses. Based on their studies, a method using the finite element method has been developed to analyze processes involving phase transformation. The method has been applied to analyze the distortion of oil-quenched gear rings. Turbat (1990) applied CA.ST.OR-2D, a FEM software developed at CETIM, for the determination of the thermal residual stresses induced in a 60NC11 steel cylinder by a quenching process, taking into account the transformation of austenite into martensite. The influence of several quenching parameters on the residual stress distribution was studied. Vansevenant (1987) proposed a mathematical model which calculates the residual stresses in surface plunge grinding. The model consists of three main parts by three separate computer programs: GRIND, TEMP and STRESS. The workmaterial thermal properties were temperature dependent. The program GRIND converts the grinding parameters (forces, speeds, wheel and workpiece properties) to heat transfer data. With the results of the previous program, the second program TEMP calculates the temperature history based on triangular input heat flux

the grinding process. This model predicts residual stresses in the workpiece and includes the residual stresses due to phase transformations in the material due to surface plunge grinding operations. However, the mechanical grinding conditions were not taken into account. Okuyama, Nishihara and Kawamura (1993) used the finite-element method to investigate thermal stresses and the geometrical accuracy of the ground surfaces produced in a workpiece during grinding. The heat flow into the workpiece, the cooling of the grinding fluid, grinding forces and the effect of magnetic chuck force were considered. Also using the finite element method, Yamakawa, Kawamura and Okuyama (1989) considered a burr-formation mechanism on a work under given grinding temperature and cutting force. Based on this, they derived the thermal and mechanical stress distributions and plastic deformation in the workpiece.

Residual stresses due to mechanical sources are attributed to interaction forces between the grinding wheel and the workpiece with iso-thermal conditions. Eda and Kishi (1986) analyzed microscopically the distribution of residual stresses in a ground surface layer with or without secondary phase grain in its matrix by the finite element method by varying the grinding parameters such as grinding force ratio (tangential force F_t *vs* normal force F_n). They showed that residual stress distribution is related to the grinding force ratio.

The combination of mechanical and thermal effects has a critical influence on residual stress development and therefore the roles of grinding interaction forces and the associated heat generated energy need to be explored. Li and Chen (1989) developed a fully coupled thermo-mechanical mathematical model which simulates the grinding process and predicts the transient temperature field and the stresses generated in the workpiece due to the constant traction forces applied and the heat produced by the grinding wheel. It also predicts the residual stress and the microstructure. Computations were performed for a workpiece in plane strain. The model calculates the temperature, stress, microstructure fields and elastic/plastic regions of the workpiece during grinding.

The random distribution of grinding wheel cutting grits, the complex nature of the contact mechanisms and chips removal can be simulated only with difficulties by FEM therefore a statistical approach may be used concurrently. Szydlowski, Weins, Gumate and Dhir (1992) developed an attractive semi-analytical method based on finite element analysis and utilized the concept of influence coefficients. The method does not require the fine division of the body into finite elements, but utilizes rather limited information on the post-grinding deformation such as changes in diameter for five different cross sections of a cylinder. The developed method was tested by Monte Carlo simulation.

The above studies were intended to examine residual stresses under different grinding conditions. However, all grinding conditions are not fully covered. To have an in-depth understanding, a more comprehensive study with theoretical modelling is necessary.

1.3.3.2 Problems Associated With Theoretical Analysis

The kinematics of the grinding process represents a series of irregular and separate engagements which depend on the microstructure of a grinding wheel as well as the geometric parameters related to the diameter of the grinding wheel, depth of cut and the type of grinding. The complex force interaction between the grinding wheel and the workpiece makes the grinding process very difficult to be modelled. Added to that, temperature rise during grinding chip formation is also difficult to control and thus the introduction of a suitable cooling (and lubricating) fluid becomes demanding.

The above complexity indicates that much attention should be paid to the following aspects: (1) grinding temperature, (2) modelling of the heat source generated by grinding, (3) modelling of cooling and (4) modelling of the contact mechanism between the grinding wheel and the workpiece. The last can be simplified by removing the grinding wheel and substituting an equivalent grinding force profile. By this the non-linearity problem arising from the contact of the grinding wheel and workpiece can be resolved. The modelling aspects (1)-(3) will be reviewed in the following sections

(1) Grinding Temperature

In recent years, considerable work has been carried out to determine the grinding temperature by developing thermal mathematical models and checking their results with experimental work. To measure the grinding temperature, different techniques were used. Chandrasekar, Farris and Bhushan (1990) measured grinding temperatures by using an infrared sensor in ferrite and steel and verified that a band heat flux moving with constant velocity was in agreement with the experiment. Kohli, Guo and Malkin (1995) reported an experimental investigation of the energy partition to the workpiece for grinding of steels with aluminum oxide and cubic boron nitride (CBN) abrasive wheels. The energy input to the workpiece was obtained by measuring the temperature distribution in the workpiece using an embedded thermocouple technique and matching the results with analytically computed values. An analysis of the results indicates that the much lower energy partition to the workpiece with CBN can be attributed to its very high thermal conductivity whereby a significant portion of the grinding heat is transported to the abrasive instead of to the workpiece. Ueda, Torii and Yamada (1994) used an optical fibre method to measure the grinding temperature in which the infrared flux radiated from the object and transmitted it to an infrared detector InAs cell. They investigated the influence of the physical properties of workpiece and grinding conditions on the grinding temperature and the thermal partition coefficient.

To predict the grinding temperature, varieties of mathematical models were also implemented. To calculate the steady state grinding temperature, a heat transfer analysis between the grinding wheel, the workpiece surface and the grinding fluids needs to be conducted. Okuyama, Nakamura and Kawamura (1993) calculated the temperature distribution in the workpiece by using the finite element method and considered the film boiling phenomenon in relation to grinding parameters. Fuh and Huang (1994) derived and verified an analytical model of the heat transfer between the grinding wheel, the workpiece surface and the grinding fluids. The model enables the prediction of the maximum surface temperature when grinding fluids are applied, demonstrates the thermal energy partitions between the abrasive wheel, the cutting fluids and the workpiece, and also determines the threshold of the occurrence of film boiling. Lavine

(1988) described a simple analytical model of the connective heat transfer between the wheel and workpiece surfaces and the grinding fluid. The model predicts the connective heat transfer coefficient at the workpiece surface, the fraction of energy entering the workpiece, and the workpiece surface temperature. Lavine and Jen (1991-A) developed a model of heat transfer in grinding that considers heat removed from the grinding zone by the workpiece, abrasive grains, and grinding fluid. The model eliminates the need to specify the fraction of the total grinding power that enters the workpiece, or the convection coefficient due to the grinding fluid. Lavine and Jen (1991-B) used a mathematical model of Lavine et al. (1991-A) to predict the occurrence of film boiling of the grinding fluid and to determine whether or not workpiece burn would subsequently occur. Jen and Lavine (1996) investigated the onset of nucleate boiling and film boiling in the grinding zone using a modified model of heat transfer in grinding which predicts the occurrence of film boiling of the grinding fluid. Chang and Szeri (1994) investigated the conditions within the grinding zone and created a self-consistent model of the thermal process in grinding which maintains distinct temperatures for coolant and grit. They calculated and verified the maximum temperature in the grinding zone, the workpiece temperature distribution, the fraction of energy entering the workpiece, and the grinding energy flux that must be reached to burn. Zheng and Gao (1994) established two thermal models, one for periphery grinding with slotted wheel and another with vertical spindle face grinding with segmented wheel in order to make selection of the slotting or segmental parameters more reasonable and to predict grinding temperature. They developed a general thermal model which not only unifies the above theoretical models but also contains Jaeger's (1942) and Des Ruisseaux's (1970) thermal models. Chiu and Malkin (1993) described a computerized simulation for cylindrical plunge grinding operations. The simulation approximately predicts both the grinding behaviour during the cycle and the final part quality, including grinding forces, power, actual material removal, temperature, thermal damage, thermal expansion, wheel wear, surface roughness and roundness. Gao and Zhenwu (1989) formulated a thermal model of grinding with a slotted wheel and a novel formula for the intermittent grinding temperature field based on the analyses of a thermal model of conventional grinding and characteristics of intermittent grinding temperature. Cooling power was considered by employing the connective heat transfer coefficient. Zhang and Faghri (1996) presented an integral approximation solution of heat transfer in the grinding process and developed a heat transfer model for the abrasive grain, fluid and workpiece. The model accounts for cases with and without film boiling in the grinding zone.

For some short grinding processes and some workmaterial properties, grinding conditions do change rapidly thereby causing a significant rise in grinding temperature which may result in workpiece damage. Therefore a transient temperature prediction is necessary. Guo and Malkin (1995) developed a thermal model for transient temperature distribution under regular and creep-feed grinding conditions. Numerical results obtained using a finite difference method indicate that the workpiece temperature rises rapidly during initial wheel-workpiece engagement (cut in), subsequently reaches a quasi-steady state if the workpiece is sufficiently long, and increases still further during final wheel-workpiece disengagement (cut out) as workpiece material is suddenly unavailable to dissipate heat. Guo and Malkin (1994) presented a thermal analysis to predict the burn-out heat flux limit at a critical temperature for film boiling. The thermal model considers the transient workpiece and fluid temperatures during a grinding pass and the energy partition to the workpiece. Rajmohan and Radhakrishnan (1992) applied heat transfer theory to the grinding process to obtain a transient model for the grinding chip temperature in dry surface grinding.

(2) Modelling of Heat Source Generated by Grinding

To overcome the necessity of workpiece and grinding wheel coupling in heat transfer analysis a moving heat flux is applied directly on the grinding zone. Shaw (1990) applied a moving heat source with a constant strength to analyze the cutting and grinding and emphasized the simplicity of analysis and application in the workshop. Zhu et al. (1995) obtained the energy input to the workpiece by measuring the temperature response in the subsurface using a two-colour infrared detector and matching the results to analytically computed values. It was found that measured temperature responses were in good agreement with analytical predictions for a moving heat source with a triangular distribution at the grinding zone. Rowe et al. (1995) measured workpiece temperatures using a 25 μm single pole thermocouple assembly and showed that measured temperature distributions in the contact zone compared best with theory assuming a square law heat flux. Jen and Lavine (1995) improved a mathematical model to analyze the heat transfer mechanisms in the grinding process and revealed that the heat flows into each of the materials are not uniform along the grinding zone.

(3) Modelling of Cooling

The power of cooling fluid plays an important role in surface integrity and residual stresses development. Des Ruisseaux and Zerkle (1970) developed a mathematical model that adds the convection heat transfer mechanism to

uniform convection heat transfer coefficient. To enhance the efficiency of cooling, cryo-cooling mechanisms were investigated. Paul et al. (1993) investigated the effects of cryo-cooling relative to soluble oil and dry grinding in respect of chip formation, grinding forces, specific energy, burning and surface characterization and indicated that the grinding temperature and burning decreased remarkably under cryo-cooling. Paul and Chattopadhyay (1996) dealt with the effect of cryogenic cooling on grinding zone temperature for five commonly used steels both experimentally and computationally and indicated experimentally that the effectiveness of cryogenic cooling is substantial.

1.4 Aims of this thesis

As discussed before, in order to meet the requirement of precise dimensions in applications, machine elements need to be ground but at the cost of an unavoidable residual stress formation. In addition to the disadvantageous residual stress effects discussed earlier in Section 1.3, there are also some advantageous residual stresses. To explore the influence of grinding conditions and workmaterial properties on the nature of residual stresses, a full understanding of the grinding stress history in relation to grinding parameters and workpiece properties is required. This motivates the need for a reliable mathematical modelling to simulate the grinding processes. The mathematical models sought should be able to predict not only the required grinding residual stresses but also the deformation history, because irreversible deformation is caused by the coupling of : (1) material non-linearity (i.e. stress-strain and/or strain rate relations), (2) geometrical non-linearity due to large deformation, (3) non-linearity introduced by the boundary conditions characterized by the mutual contact between the grinding wheel and the workpiece, and (4) the dependence of material properties on temperature.

The objective of this thesis is to build up a reliable finite element model for grinding-induced residual stress analysis and thus to explore thoroughly the mechanisms in terms of grinding conditions. Specifically, it will

1. investigate the grinding temperature in relation to thermal grinding parameters and thermal workmaterial properties,
2. study the thermal residual stresses including the effect of phase change,
3. analyze the mechanically induced residual stresses under iso-thermal grinding conditions,
4. combine the individual effects of grinding condition coupling on residual stress distributions and
5. discuss the favourable grinding conditions for beneficial residual stresses.

To overcome the mathematical modelling difficulties, ADINA, a well-known finite element method commercial package, will be implemented to account for numerical calculations and associated solution convergence. However, special attention will be paid to simplify the contact problems between the grinding wheel and the workpiece by removing the grinding wheel and substituting the proper associated interaction forces directly on the workpiece through the grinding zone.