THE SPRING RESEARCH AND MANUFACTURERS' ASSOCIATION

NON-CONVENTIONAL TECHNIQUES OF METAL REMOVAL FOR THE FORMATION OF SQUARED END COILS IN HEAVY SPRINGS

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SUMMARY

A literature survey has been carried out to identify the most promising techniques for the rapid formation of squared end coils on heavy compression springs in the near future. Of the five possible techniques investigated, coated abrasive belt machining and abrasive cut-off techniques show the most immediate promise, already being potentially more competitive than conventional end grinding, in terms of faster spring grinding at approximately equivalent costs per spring.

High speed grinding is likely to increase in importance in the future, but considerable development remains to be carried out before a commercial machine becomes available, especially in view of the considerable guarding arrangements necessary for operator safety at wheel speeds in excess of 45 m/s.

Plasma arc cutting equipment is also now available at reasonable cost, but laser beam techniques await the development of suitable CO_2 lasers, the price of which may be prohibitive for the immediately foreseeable future.

Consideration of the metallurgical effects associated with these five techniques has indicated that both coated abrasive belt machining and abrasive cut-off techniques result in very little metallurgical damage to hardened and tempered spring steels, in terms of re-hardened or overtempered and softened surface structures, and little or no subsequent equalization is therefore required.

High speed grinding can result in some metallurgical damage, which may be up to 240 μm in depth, in the absence of correct and/or adequate coolant/lubricant arrangements.

Plasma arc and laser beam cutting produce heat affected zones of up to 5 mm and 1 mm respectively, and springs would require some degree of equalization after the formation of the end coils.

Coated abrasive belt machining and abrasive cut-off techniques have therefore been identified as the two most promising processes for the rapid formation of squared end coils in heavy springs.

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1. INTRODUCTION

End grinding has always been recognised to be one of the slowest operations in the manufacture of heavy springs(1,2). The formation of satisfactorily flat end coils is nevertheless often necessary, in the absence of special locating arrangements, if the springs are to obtain a good seat against a mating part whilst resisting sideways deflections and exerting a more uniform axial force under load.

The problem can be particularly acute in the case of heavy springs, where a considerable volume of metal may have to be removed to produce spring ends which are squared to the spring axis over 270°, as specified in DIN2096 for example.

Techniques widely used for this purpose at present include conventional end grinding of the springs using currently available equipment and taper rolling/forging of the bar stock ends prior to coiling. The latter process produces a sound metallurgical structure, with very good grain flow characteristics, but involves accurate location of the bar ends during coiling, to obtain the required end coil positional relationships, together with a possible equalising grinding operation after coiling.

In view of the recent developments in metal removal/cutting processes which have occurred in the last few years, however, it was considered propitious to re-examine the means by which end coils of such springs might be more rapidly squared, whilst carrying out an assessment of the associated alterations in the metallographic structures which might necessitate equalising grinding for the particular processes considered.

It should be pointed out that some of the techniques would involve the development of appropriate equipment and ancillary support systems, so that it is often not possible, at this stage, to give comprehensive breakdowns of the economics involved, other than consideration of the initial capital costs entailed in the purchase and development of the systems investigated.

2. TECHNIQUES SUITABLE FOR FORMATION OF SQUARED SPRING ENDS

In the context of present day spring making economics and available technology, the following processes are capable of high rates of metal stock removal, and can therefore be considered as possible alternatives to conventional spring end grinding.

1. High Speed Abrasive Grinding
2. Parting by Abrasive Cutting
3. Coated Abrasive Belt Machining
4. Parting by Plasma "transferred" arc cutting
5. Parting by Laser Beam Cutting

2.1 High Speed Abrasive Grinding

Conventional grinding generally takes place at surface cutting speeds within the range 15-30 metres/second.

Recent research into possible ways of increasing grinding productivity, however, has led to the development of high speed grinding techniques, which could yield a several fold increase in the rate of stock removal,(3,4,5,6). A typical example given in the literature states that increasing the wheel speed from 30 m/s to 80 m/s reduces the grinding force, and increases the metal removal rate by 3-4 times in the case of materials of good grindability, such as carbon-chromium bearing steels, without significant increases in workpiece surface temperatures. In contrast to this behaviour, however, materials which are difficult to grind conventionally, such as the stainless steel and nickel based alloys, do not show the same marked increases in metal removal rates, but do exhibit significant increases in workpiece surface temperatures(7,8).

Many of these investigations are being carried out under the auspices of the Science Research Council, in the form of a Programme of Grinding Research, and developments here would merit close attention in the future (3).

At present, however, the use of high speed grinding techniques essentially necessitates the development and construction of suitable machines with appropriate stiffness, bearing design and power characteristics. Furthermore, it has recently been suggested that decreased grinding time alone is not the sole arbiter of production, the overall grinding economics being very strongly influenced by the stock removal ratio, G, (Volume of metal removed : Volume of wheel removed), dressing intervals (if any) and the down time necessary for wheel adjustment and replacement (9).

2.2 Parting Off by Abrasive Cutting

The use of abrasive cut-off techniques for the formation of squared ends in heavy springs has already been reported in the literature (10). The technique involved the simultaneous formation of both squared end coils by dry abrasive cutting, and was claimed to save machining time when compared to the conventional end grinding of heavy springs, since the greater part of the excess material was removed unchipped. Furthermore, the machine was designed so as to cut the spring progressively, whilst the latter rotated relatively rapidly about its own axis, and hence cutting temperatures were kept to a minimum whilst little or no equalising grinding operations were necessary after parting. A relatively complicated clamping system was necessary, however, to prevent distortion of the spring during cutting, and hence longer times were required for resetting from one spring design to another.

Nevertheless, it was claimed that the increase in output made the process an attractive economic proposition when compared with the overall costs of conventional spring end grinding.

No mention was made of machine or development costs, but normal radiac type machines of a design suitable for this type of development would cost approximately £20,000 (11).

2.3 Coated Abrasive Belt Machining

Coated abrasive belt machining (CAM) is basically an abrasion technique which uses specially prepared belts in conjunction with machines capable of applying over 100 kW of power during the cutting process.

It is claimed that these machines can have metal removal rates which are significantly faster than the equivalent, more conventional grinding operations, since the process utilizes belts coated with tough zirconia-alumina grits, which are electrostatically deposited onto an adhesively sized cloth backing to give the best orientation for cutting in one direction (12,13,14). Metal removal rates of up to 80,000 mm^3/min for high speed steel hardened to Rc70 (HV1000) are typically quoted in the literature (15).

Furthermore, research has indicated that individual belts can have an economic life, with wear of the abrasive being monitored by a simple measurement of belt thickness (16).

Whilst coated abrasive belt machining costs can only be estimated it has been suggested that a machine suitable for end grinding of springs, made from 30-50 mm diameter wire would cost £10,000-£12,000. With inhibited water as a coolant, the cycle time would be approximately 28 seconds per spring end (13 seconds grinding plus 15 seconds handling) whilst the flatness and surface finish would be approximately 0.13 mm and 51 μm respectively. One abrasive belt would grind approximately 30 spring ends (i.e. 15 springs). A price of approximately 80p per spring has been suggested as a possible costing for end coil grinding using coated abrasive belt machining. This compares favourably with the present (approximate) price of 60-90p per spring when the ends are ground on a Snow grinder, for example.

Whilst these costs can only be considered as very approximate at this stage of development, they indicate that CAM could become competitive with conventional grinding techniques, especially when it is remembered that CAM may have the potential for 3-6 times the production rate of conventional grinding. The CAM process is now under active development for end grinding of heavy springs in the U.K.(17).

2.4 Parting off by Plasma Arc and Laser Beam Cutting

Plasma "transferred" arc cutting essentially utilizes a narrow, high velocity jet of ionized gas (usually an Argon/Hydrogen mixture), at a temperature of approximately 20,000°C, to locally melt the metal and simultaneously disperse the molten metal produced. Since no oxygen is used in the process, the cutting action is totally dependent upon the heat generated by the arc, leading to the development of a relatively narrow cutting gap, or kerf width, of between 3-4.5 mm for 20 mm thick and 60 mm thick alloy steel respectively. The cutting rate can be up to 400 mm/min for 20 mm steel, reducing to 150 mm/min for metal of 60 mm thickness(18).

The process has been well established in Europe for some 20 years, and plasma torches, together with the necessary ancillary equipment, are readily available. A basic torch plus ancillary systems for cutting 60 mm bar would cost approximately £10,000 at the time of writing(19).

In Laser Beam Cutting, the output of a continuous beam laser (typically a carbon-dioxide laser with an output within the range 0.4-5.0 kW) is focussed onto or slightly below the surface of the steel workpiece to give a spot size of approximately 200 μm. A stream of oxygen gas is simultaneously directed axially down the laser beam onto the metal surface.

The radiation energy of the beam is partly absorbed by the metal surface, producing local melting, and this immediately initiates a rapid chemical reaction between the iron base and the oxygen with further generation of heat, whilst the molten metal/oxide is swept aside by the gas stream(20). Cutting speeds can be up to 720 mm/min for 10 mm diameter silver steel bar, using a 5 kW continuous CO_2 laser with air-jet assistance, giving kerf widths of approximately 1 mm(21).

Such laser systems are expensive, however, with costs of £70,000-£75,000 for a 2 kW system. Power outputs in excess of 5 kW would be necessary to cut steels up to 20 mm diameter, and the projected cost of such a system would be approximately £200,000 at the time of writing.

In view of the high capital costs associated with laser beam technology at the moment, therefore, such systems would appear to be unlikely candidates for adoption in the spring industry as replacements for conventional end grinding of heavy springs. One author has recently confirmed that, for cutting alloy steels in the range 3-150 mm thickness, the plasma "transferred" arc process must be considered as a viable alternative to laser beam cutting(22).

It is of interest, however, to note that CO_2 lasers of 0.4 kW output are at present in use for profile cutting of spring steel sheet(23).

3. METALLURGICAL CONSIDERATIONS

For a cutting/grinding process carried out on a typical spring steel, such as 250A53 (En 45) at room temperature, the metallurgical effects of that process will be largely determined by the maximum temperature of the generated surface.

In general terms, maximum surface temperatures above those at which the steel was tempered, but below approximately 800°C, will lead to varying degrees of overtempering and subsequent softening of the material at and near to the cut surface. Maximum temperatures greater than 800°C, however, can result in the formation of austenite at the surface whilst cutting/grinding is in progress. The high cooling rates, of the order of 1,000-2,000 C per second, subsequently associated with the mass quenching effect of the adjacent cold metal will then result in the formation of a fully hardened layer of brittle martensite from the austenite, at the steel surface, and an overtempered, softened structure below this re-hardened layer(24).

It will be necessary to remove this Heat Affected Zone (HAZ), of course, by an equalising (grinding) operation before the spring is put into service, and the costs of this operation will be additive to those incurred by the original cutting/ grinding operation.

3.1 Heat Affected Zones Formed During High Speed Grinding, Abrasive Cutting and Coated Abrasive Belt Machining

Many factors will contribute to the surface temperatures encountered during abrasive cutting/grinding of hardened and tempered alloy spring steels at high wheel speeds. These include the type of wheel employed, the grinding force applied, the characteristics of the particular abrasive process employed and whether the process is carried out dry or with a coolant/ lubricant.

Investigations into the effects of coolants on the Heat Affected Zone formed during conventional grinding of several hardened alloy steels of the 534A99 (En 31) 1% C 1% Cr type have shown that grinding at a peripheral wheel speed of 30 m/s without coolant can result in the formation of a surface layer of virgin martensite to a depth of approximately 30 µm, with a further overtempered and softened zone of approximately 45 µm, giving a total HAZ of approximately 75 µm. The use of a soluble oil and water emulsion mixture as coolant/lubricant resulted in overtempering only, however, to a depth of 30 µm, the formation of martensite at the surface being avoided completely(25).

Similar investigations under conditions of high speed grinding, at a peripheral wheel speed of 60 m/s. have shown that use of a 7% soluble oil and water coolant, during grinding of a hardened and tempered 735A50 (En 47) alloy steel, gave a fully rehardened zone of brittle martensite to a depth of 360 µm, with a further overtempered and softened zone at least as great again, giving a total HAZ of approximately 700 µm. By contrast, the same steel ground under similar conditions using neat oil as a grinding fluid was fully re-hardened to a depth of only 50 μm, with a further overtempered zone of 190 μm, giving a total HAZ of approximately 240 μm(26). The importance of using an appropriate grinding fluid can therefore be clearly seen.

The action of coolant/lubricant fluids in grinding has been considered in detail be several investigators, and it has been generally noted that the major effect of a well chosen grinding fluid and delivery system is to reduce the heat generated during grinding, in addition to actually removing the generated heat from the grinding zone(27,28,29,30).

The general conclusions to be drawn from these investigations therefore suggest that a grinding fluid should be used during high speed grinding, and that neat oil is to be preferred if substantial heat affected zones are to be avoided. High speed grinding can still result in overtempered and softened structures to a depth of up to 240 μm, however, even when neat oil is used as a grinding fluid.

These investigations also resulted in a comparison between the thermal effects of surface grinding and abrasive cut-off techniques upon a hardened and tempered alloy steel workpiece(29). The work suggested that approximately 60-95% of the energy consumed during grinding flowed instantaneously into the workpiece to yield considerable and rapid increases in the surface temperature. In terms of the specific energy (the energy required to remove unit volume of metal), however, abrasive cut-off processes tended to need only 10-20% of the energy input required for conventional grinding, and hence the metallurgical effects of abrasive cut-off techniques were less marked than those produced during grinding.

The dissipation of the heat generated, into the appropriate surroundings, was also substantially different for the two processes, and could be represented very approximately as follows:

Energy Sink	Energy Absorbed During Cutting Process (%)	
	Abrasive Grinding	Abrasive Cut-off
Metal Chips	10	60
Metal Workpiece	73	10
Cooling System	7	10
Abrasive Wheel	10	20

Hence metallurgical damage is inherently less likely to result from the use of abrasive cut-off techniques rather than surface grinding processes.

A further interesting finding, was that, during abrasive cut-off grinding, increased force application achieved the dual purpose of both increasing the cutting rate whilst actually further reducing the temperature of the cut surface. This technique therefore produced extra benefits in the form of lower workpiece surface temperatures at very high metal removal rates provided, of course, that the machines were of sufficient power and stiffness, and the abrasive discs were of appropriate quality.

Various claims have been made concerning the thermal effects associated with the coated abrasive machining processes which are now available for rapid stock removal(12,13,14,15,16,17,31,32). The general conclusions to be drawn, however, are that wet abrasive belt machining produces approximately half the heating effect of high speed grinding at equivalent high rates of metal removal. Furthermore, approximately 90% of the heat generated in abrasive belt grinding is claimed to be dissipated into the chips produced, so that the metal surface remains relatively cool, with heat affected zones generally less than 70 µm in total depth.

3.2 Heat Affected Zone in Plasma Arc and Laser Beam Cutting

The available evidence for these two cutting techniques suggests that they both produce relatively substantial heat affected zones, consisting of an overtempered, softened structure below a brittle, martensitic zone at the surface. In general, plasma arc cutting, can produce HAZ of up to 5 mm depth, which contrasts with the 1 mm deep HAZ produced during laser cutting(21,33,34).

The latter process would thus appear to give better results than plasma arc cutting for alloy steels but, of course, the powerful lasers necessary for cutting steel bars in excess of 20 mm diameter are still under development, and will probably remain an expensive investment for the immediately foreseeable future.

4. CONCLUSIONS AND RECOMMENDATIONS

Based on the results of this literature survey, the following techniques are potentially suitable for the rapid generation of flat ends on heavy compression springs.

1. Coated Abrasive Belt Machining
2. Abrasive Cut-off
3. High Speed Grinding
4. Plasma Arc Cutting
5. Laser Beam Cutting

The first two items have the advantage of effectively yielding high metal removal rates whilst necessitating little or no equalizing operations.

Furthermore equipment suitable for development is now commercially obtainable at prices which compare very favourably with the £30,000 (approximately) investment required for a typical commercial end grinding machine suitable for springs made from 40 mm diameter wire.

The use of abrasive cut-off techniques for spring end coil formation has already been documented and hence some guidelines to its development as a process are readily obtainable, whilst technical and commercial assistance is available for coated abrasive belt machining techniques(10,17).

High speed grinding may be a viable alternative to conventional end grinding in the near future, but requires the development of suitable machines of adequate stiffness and bearing design, together with the incorporation of recent developments in coolant delivery systems(30,35). Safety considerations for operating personnel are important in the development of high speed grinding, since special guarding arrangements are required to cover eventualities such as wheel burst. This aspect of operator safety becomes particularly important at wheel speeds in excess of approximately 45 m/s., since the kinetic energy of the moving fragment increases with the square of the rotational velocity(36).

In the field of flame cutting, plasma arc techniques again have the advantage that the basic equipment is readily available at reasonable cost, as compared to that for laser beam cutting, where development costs may result in a final investment in excess of £200,000.

The plasma arc process produces a relatively large heat affected zone, however, and could therefore require an extensive equalizing operation after cutting, which could serve to increase the overall cost per spring and thus mitigate against adoption for spring end formation.

In conclusion, therefore, the most likely areas for developments in non-conventional end grinding of heavy springs for the near future would appear to be in the fields of Coated Abrasive Belt Machining and Abrasive Cut-off techniques respectively.

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