A NOVEL TECHNIQUE FOR DRIVELINE ASSEMBLY APPLICATIONS

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Abstract

A novel technique for drivetrain assembly - Mill-Knurling and Press-Fitting (MKPF) is projected as a substitute to laser welding or bolting. This joining practice involves the press fitting of two mating surfaces, one with mill-knurled teeth and the other which is of a comparatively softer material, enabling it to stream over the teeth making a joint. This process has been applied within an automobile rear axle differential which is subjected to random torque loads. Experimental analysis and simulation has been used to evaluate the serviceable viability and the latent benefits of mill knurled joints with both laser welded and bolted joints currently used by BMW.

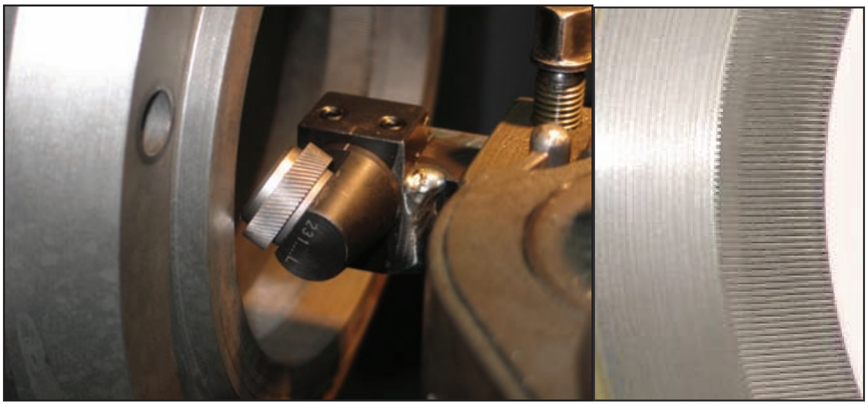
Assumptions such as total cost of planning, research and development, total investment, total specific resources, raw material and manufacturing costs were used to evaluate mill knurling as an alternative to laser welding and bolted assemblies.

The MKPF method has been successfully applied to assemble rear axle differential cases to the bevel gears. The costs, weight and size estimations are very positive in comparison to the competitive methods of laser welding and bolting. The noteworthy weight saving will strengthen the efforts by the automotive industry to reduce the emission levels of vehicles. The pitch flank deviation values which are critical for the life cycle duty of the bevel gear need to be further investigated in order to achieve comparable results with laser welding.

Keywords: *transport, road transport, simulation, driveline, manufacture, press fit*

1. Introduction

In its pursuit for ever-increasing fuel effectiveness and reducing emissions and carbon footprint, the Automotive industry is constantly seeking innovative methods of mass construction that can reduce the weight and size of components and assemblies. By the year 2012 the European Automotive Manufacturers Association (ACEA) are urging all automotive manufacturers to meet the average 130g/km legislation. Automotive manufacturers that do not act in accordance with these legislations will be obliged to pay a fine [1]. There have been most important developments and breakthroughs during recent decades in new materials and their manufacture, such as hydroforming [2] and laser welding [3] that has contributed appreciably to achieving the above objectives. This paper reports a new method of assembly for the vehicle drivetrain components here described as – mill-knurling and press-fitting (MKPF) – with the intention of further reducing the size, weight and thereby the cost of the current processes namely laser welding and mechanical fastening. This new procedure involves imparting a knurled surface by milling on one of the component’s surface (Fig. 1). The knurl pattern comprises fine triangular teeth of 0.4 mm height and 1mm pitch. The mating component remains in its original ‘‘soft’’ state. The component with the mill knurled teeth is then pressed on to the mating component in an axial direction to make interference fit. Thus the joint is formed by the action of the unhardened material plastically flowing over the hardened knurled teeth.



(a) (b)

Fig. 1. (a) Milling knurl pattern on a mating surface; (b) Knurled surface on the bevel wheel

2. Process application

2.1. Assembly of rear axle differential

A typical BMW car rear axle differential uses a bolted bevel wheel differential case assembly formation as shown in Fig. 2. This bolted assembly method is gradually being replaced with laser welding. Laser welding enables a more compact joint than the bolted one as can be seen in Fig. 3, thus reducing the weight, the number of components and the overall size. Other OEMs such as Volkswagen AG are following suit by adopting laser welding instead of a bolted type [4].

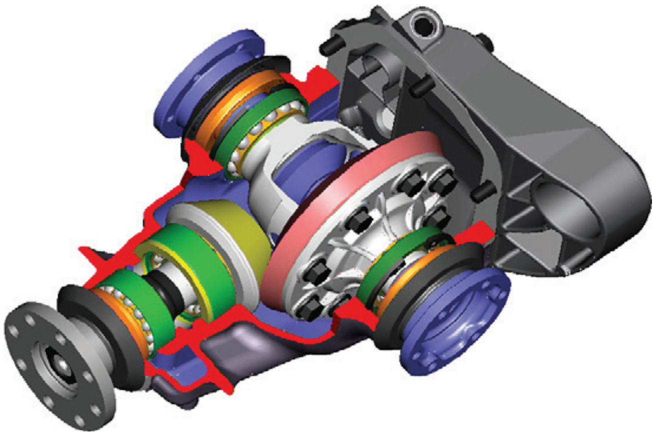
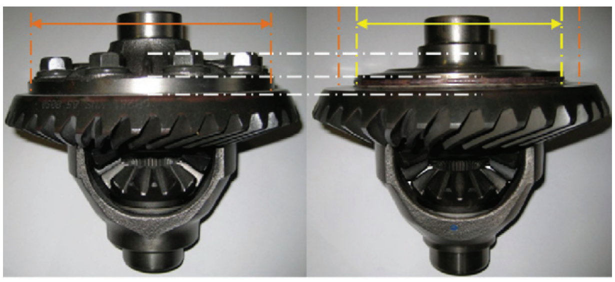


Fig. 2. A typical BMW rear axle differential



(a) (b)

Fig. 3. Assembly- (a) Bolted (b) Laser welded

2.2. Mill-Knurling and Press-Fitting (MKPF)

Although laser welding has yielded the desired benefits over the bolted assembly concerning size and weight reduction, there are also some drawbacks related with laser welding. According to Daub et al. (2000) [5], in laser welding not only are there high investment costs and heat deformation effects that must be considered, there are also many other critical factors that must be tightly controlled in order to ensure that the correct weld seam is maintained. These factors include class of material grade, material cleanliness, geometrical accuracy, alignment and pre-assembly of the components. Thus, an alternative method of assembling the bevel wheel with the differential case is still being sought. The notion of MKPF as a method of bonding originated from the BMW Plant in the Landshut Prototype Development Department [6]. The cost saving potential of MKPF compared to laser welding was instantly apparent as the elevated cost of an automated laser welding machine could be avoided with a simple automated turning centre. It was envisaged that MKPF could also offer further size and weight improvement over laser welding. It was determined to use a triangular geometry as shown in Fig. 4 (knurl type RAA, the depth was set to 0.4 mm and a pitch of 1 mm) for this application. The tooth parameter for the given internal diameter allowed 414 teeth to be manufactured. The role of these teeth is not only to facilitate the joining process to occur, but also, to act as a source of torque transfer from the bevel wheel to the differential case and then directly to the driven wheels. The standards used as references within this investigation were DIN 82 [7], DIN 403 [8] and the knowledge base supplied by the tooling manufacturer, Quick [9]. In Fig. 5, the assembly approach is presented.

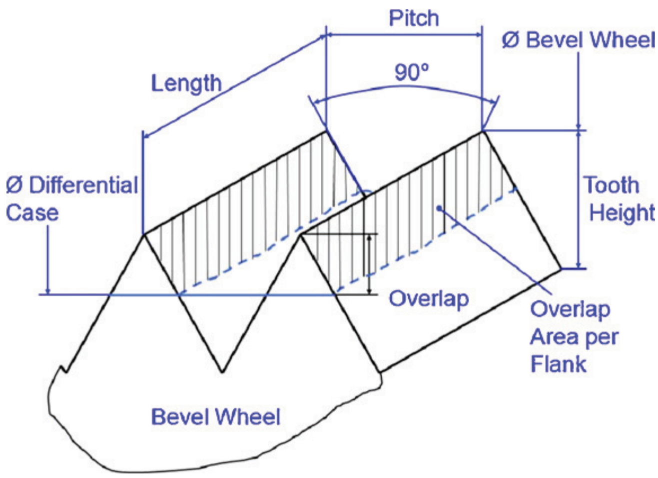
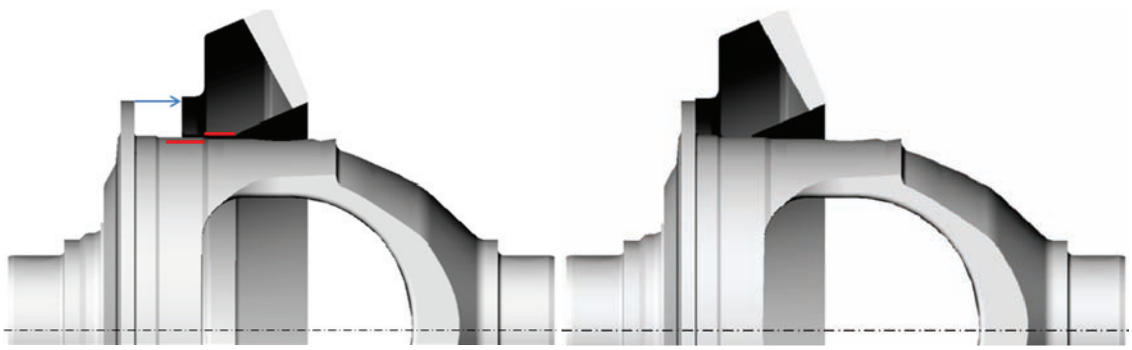


Fig. 4. A milled knurl tooth parameter including the parameter of the mating part



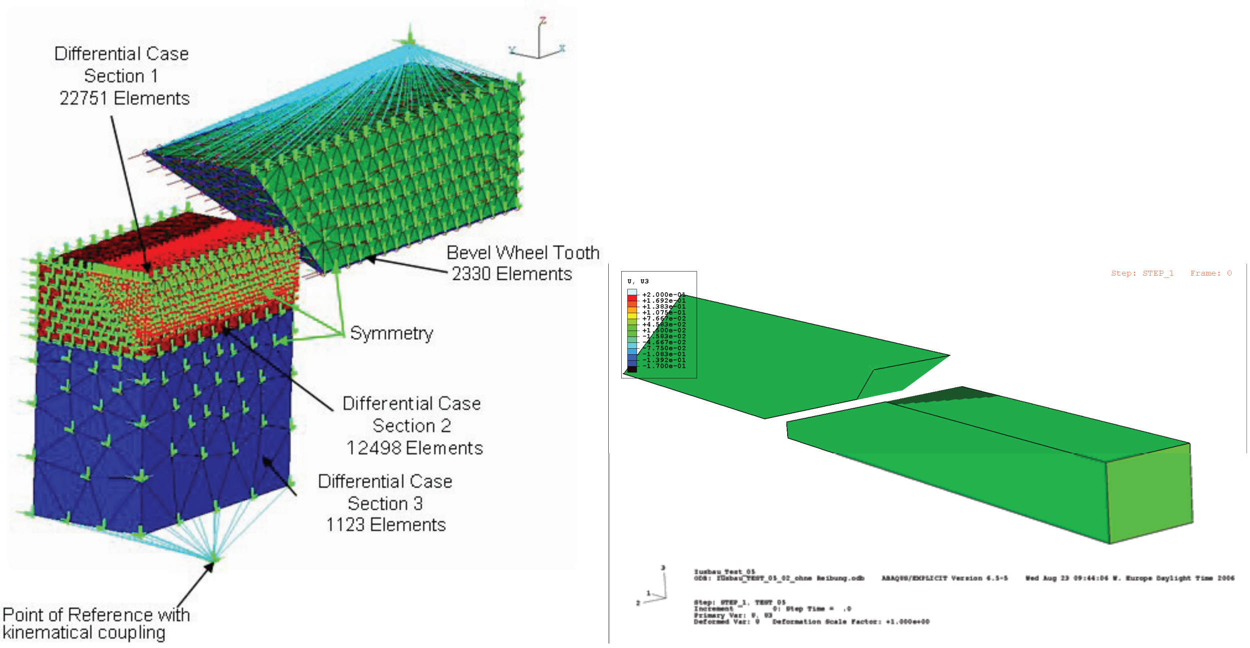
a) b)

Fig. 5. Initial step of assembling bevel wheel to differential case, piloting, before the securing means per laser weld or in some cases by use of bolt fixture is applied. a) Pre-piloting starts – areas marked in red, b) both parts are piloted to each other

3. Simulation

3.1. Material flow simulation

There is little literature on an assembly process using a MKPF, therefore, modelling and simulation of milled or rolled knurl joints were undertaken to gain some insight into the process. Slomchack [10] discusses the problems associated with theoretical and experimental investigations of the deformation process in rolling. The simulation methods or pressing of a specimen with milled knurl teeth to a work piece of a different material was developed with the aid of CATIAV5 and ABAQUS Explicit. In order to establish the deformation process and to attain the scale of stress caused through the assembly, the modelling was conducted in three stages. The first stage was to comprehend the material flow and the forces fashioned during the assembly process. The next stage was to use the simulation methods to establish the torque transfer on the knurled teeth. As the results were satisfactory in the first two stages a third stage was carried out to identify the plastic deformation within the area of the bevel gear teeth during the assembly of bevel gear and differential case, from which, the contact patch deviation was determined. Fig. 6 illustrates examples of the FEA and the assembly simulations. The simulation results were contrasted with the micrographs of the real test samples of the mill knurled joints (Fig. 11 and 12). The simulation work shows how and where the ductile material from the differential case flows due to the deformation action caused by the pressure from the harder material of the bevel wheel. From Fig. 6(b), the deformation of the ductile material can be described as being similar to a “bow wave” from a sailing vessel. A close correlation between the simulated and the micrograph section cuts can clearly be seen.



(a) (b)

Fig. 6. Model of one half of a tooth geometry used in the ABAQUS calculations (a) FEA model, (b) Assembly simulation

3.2. Assembly force analysis

The material flow simulation demonstrated that the assembly forces were greater than the current assembly values in production. Fig. 7 shows the results of the assembly forces from the material flow simulation.

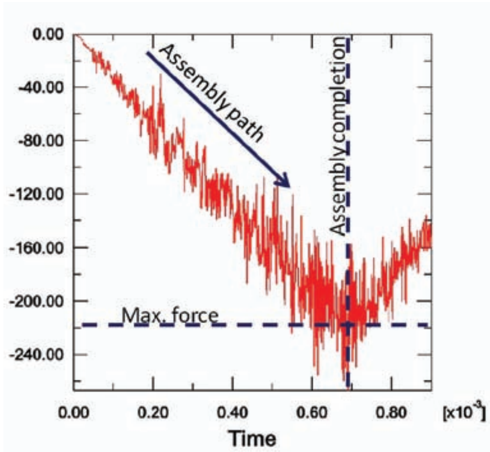
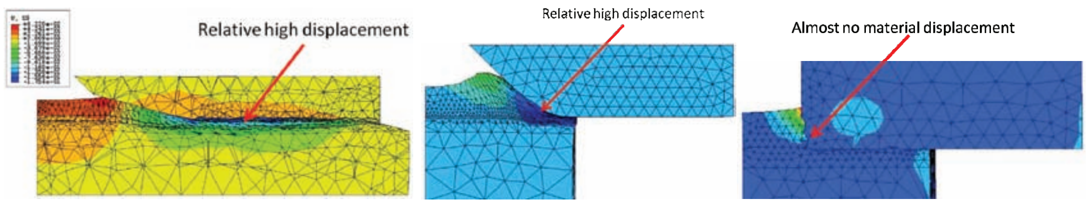


Fig. 7. Assembly forces taken from the material flow simulation for one half of a tooth. The chamfer geometry was found to be the foremost factor for the assembly forces and hence various designs were investigated as can be seen in Fig. 8 and with the results shown in Tab. 1



a) b) c)

Fig. 8. Material displacement and assembly forces with respect to the cutting angle of the milled knurl tooth, (a) 15°cutting angle, (b) 45° cutting angle and (c) 90° cutting angle

Tab. 1. Summary of the calculated assembly results

Chamfer Angle [°]	Reaction Force per half a tooth [N]	Assembly Force required in Tonnes for complete Differential wheel [Tonnes]
15	440	37
45	220	18.6
90	120	10

It can be observed that the sharper the angle at the cutting plane of the teeth the less force is required to assemble the bevel wheel to the differential case. The chamfer needs to be as sharp as possible in order to sustain the assembly forces to a minimum, this angle being 90° to the centre of axis of the work piece.

4. Experimental setup

The existing mass production process was considered in the experimental hardware geometry in order to incorporate as much as possible and thereby minimise investment costs. Past experience has shown the importance of conducting trials as near to manufacture as possible. The tooling consisted of a simple economical cutter that was mounted on an automated lathe to generate the required geometry. For mass production a CNC machine with automatic part feeding would be specified. Although the process is simple, the assembly of the bevel wheel and the differential case must be carried out to a high degree of accuracy in order to fulfil the gear tooth contact patch required to maintain the low noise and the high duty cycle of the rear axle differential. Thus, the bevel wheel and the differential case must be assembled to an absolute minimum run out tolerance, a few hundredths of a millimetre. For the experiments each assembly of bevel wheel to differential case was carried out individually and manually. For full production, however, a fully automated process similar would be specified. Loads in the region between 8 and 38kN were required to fully assemble the two components together by MKPF in the trials, an example can be seen in Fig. 9 and summarised in Tab. 2. As per the simulation, the major factor that influenced the assembly force was the chamfer geometry of the bevel wheel. The 8kN being slightly more than the current assembly force of 7kN for a laser welded assembly. The aim with the mill knurl press fitting is to push the soft ductile cast iron into the small gaps underneath the overlap area seen in Fig. 4 to create a 100% filling ratio. The more material between the flanks of the milled knurl tooth the more accurate is the computation for torque transfer.

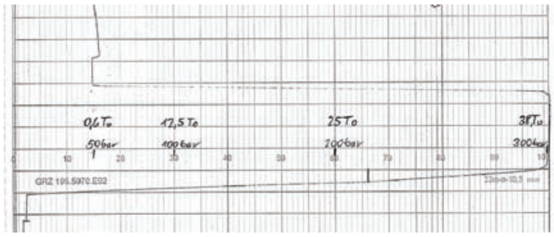
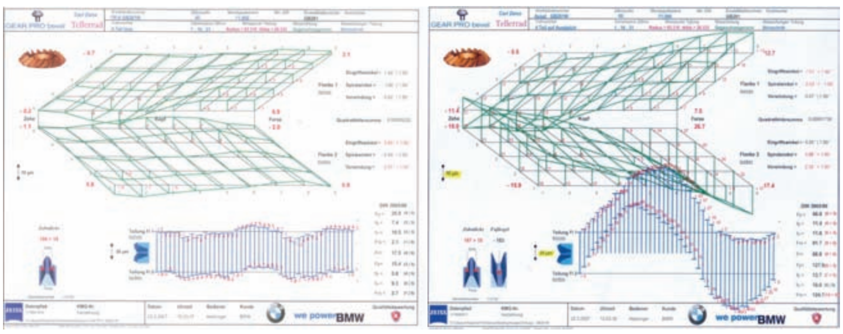


Fig. 9. Force over distance recording from a mill knurl press fitting, parts being the differential case and bevel wheel

Tab. 2. Summary of the calculated and hardware assembly results

Chamfer Angle [°]	Assembly Force per simulation [Tonnes]	Assembly Force per Hardware trials [Tonnes]
15	37	38
45	18.6	20
90	10	8

Although the design, manufacture and assembly procedure are precisely the same for the bevel wheel and the differential case, there was some departure in the measured forces. This can be ascribed to the perpendicular alignment of the mating surface and the assembly axis not being alike to each other and hence requiring additional force to overcome the formation of teeth by plastic flow in the differential case. In spite of pre-piloting the parts it seems that micro deviations can still occur during the press process of bevel wheel to differential case. The deviation of the perpendicular alignment between the mating surfaces and the assembly is further verified by the tooth flank pitch measurements taken on the bevel wheel before and after assembly as shown in Fig. 10, where, Fig. 10(a) shows gear tooth measurement before the assembly and Fig. 10(b) shows the same tooth after assembly. In sum, three teeth, approximately 120° apart from each other, were measured on the bevel wheel. The blue grid shows the perfect tooth flank profile and the green grid shows the measured profile of the tooth. The differences between the two grids characterize the delta between the perfect gear flank geometries and the machined state.



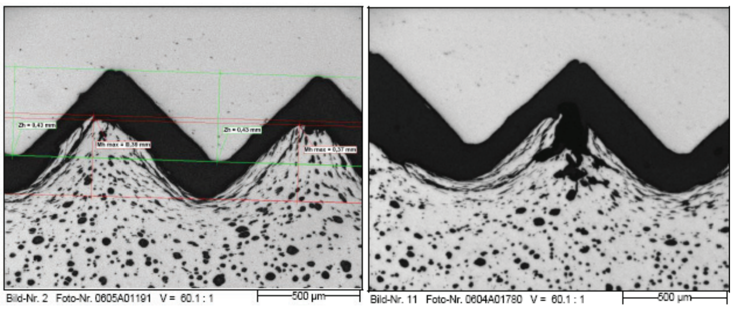
(a) (b)

Fig. 10. Flank pitch measurements taken before assembly (a) and after assembly (b)

The simulation work, torque transferability tests were conducted in parallel. With the aid of a test rig, fluctuating load cycles and a series of shocks, i.e., sudden application of torque was used to test MKPF assemblies. This being required to establish the practicality of the assembly in close to reality shock load tests before it can be passed for supplementary testing within the vehicle. The fluctuation test rig testing certified a series of tests with variations of mill knurled tooth length with and without the use of adhesives to be carried out with loads up to ±5KNm over a defined period of time. The fluctuating test rig was not able to test a complete differential transmission which allowed the test to concentrate on the joining area only. The next stage comprised the MKPF to be tested in a complete differential transmission and also on one of the harsher test programmes called the shock test. A shock test comprises of spike loadings which are transmitted through the driveline simulating wheel spin in first gear with a high coefficient of friction between road wheel and vehicle tyre. The torque being transmitted through the differential case is circa 11KNm. The knurl teeth length tested ranged from 3–12mm. There were no failures in any of the assemblies, indicating that MKPF joints can successfully withstand and transfer loads, in a similar capacity to that of laser welded or bolted assemblies.

5. Results and discussion

In order to evaluate the process mechanism of MKPF, polished micrographs were taken from section cuts which are shown in Fig. 11. It can be seen from these that the teeth generated on the differential case are more or less a mirror image of the knurled teeth of the bevel wheel. This is because the hardened, sharp profile of the milled teeth on the bevel wheel cause the softer material of the differential case to plastically flow into the gaps of the knurl profile, enabling an almost ideal fit between the two parts. The filling ratio was in the range of 90%. The dimensions of the formed teeth on the differential case are easily measured and show that tooth to tooth are relatively similar and hence an average tooth geometry for the differential case can be supposed. It was also observed that no deformation on the hardened bevel wheel tooth geometry took place and no signs of cold welding on the parts were evident. Furthermore, only a very few signs of burrs were noticed during the press assembly.



(a) *(b)*

Fig. 11. Section cut and glued together by means of Loctite (black section) (a) showing good filling properties and distribution of spherical graphite in the cast iron GJS-600; (b showing poor filling properties

Figure 12 shows sample micrograph section cuts taken from laser welded and mill knurled joints. It can be seen that the laser welded joint has a more clearly defined interface than the mill knurled joint. The advantage of having a better definable interface between the components is that it reduces the tolerance band or the safety factors used in torque transfer calculations. This indicates that mill knurled joints need higher tolerance margins. It was estimated that the filling ratio for MKPF joints are approximately 90%, whereas for laser welded assemblies it was 99%. However, from the torque transfer experiments, no unfavourable results were observed for the MKPF assemblies. In terms of size and weight, MKPF surpasses the laser welded assembly. The width of the bevel wheel differential case assembly can be reduced by 4 mm. The weight saving on the bevel wheel which depends on the gear ratio is between 370g and 740g. The dimension of the assembled differential case with bevel wheel in turn dictates the total width of the rear axle assembly, which may also be reduced by 4 mm. A width reduction of 4mm for a cast iron or aluminium housing yields a weight saving of approximately 220g and 80g, respectively. The only part that remains neutral in terms of weight is the differential case. Depending on the gear ratio, therefore an overall weight saving between 450g and 960g is possible with MKPF compared to a laser welded assembly.

6. Business case

Assumptions such as total cost of planning, research and development, total investment, total specific resources, raw material and manufacturing costs were used to evaluate mill knurling as an alternative to laser welding and bolted assemblies. With regard to a laser welded assembly a total saving of approximately €450,000 is achievable within the product cycle of three rear axle variations that have the same service life time period. Since it has been proven that laser welding is more cost effective than bolting BMW is already changing from the latter. Compared to bolting the MKPF assembly can yield greater savings. For example, a MKPF joint has 10 fewer parts than a bolted one and in addition, the elimination of adhesives currently used is advantageous. In terms of machining processes the mill knurled joint has two fewer operations than the bolted assembly giving extra advantage in production time.

7. Summary

The MKPF method has been successfully applied to assemble rear axle differential cases to the bevel gears. The costs, weight and size estimations are very positive in comparison to the competitive methods of laser welding and bolting. The noteworthy weight saving will strengthen the efforts by the automotive industry to reduce the emission levels of vehicles. The pitch flank deviation values which are critical for the life cycle duty of the bevel gear need to be further investigated in order to achieve comparable results with laser welding.

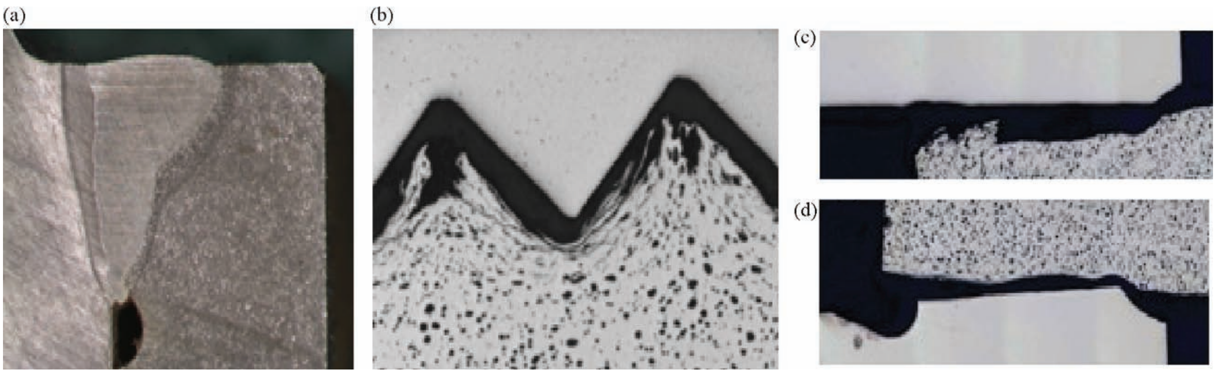


Fig. 12. Polished micro-section cuts: (a) Laser weld seam between the two parts, (b) Mill knurled across the teeth, (c) Section cut along the tooth dedendum, (d) Section cut along the tooth addendum

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