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An open report for the project

Ultra high strength and ultra clean steel for light weight fasteners

Project within sustainable production technology

Vinnova document number 2010-02831

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Date 2013-03-28

New generation of fasteners B14

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Content

FFI in short

FFI is a partnership between the Swedish government and automotive industry for joint funding of research, innovation and development concentrating on Climate & Environment and Safety. FFI has R&D activities worth approx. €100 million per year, of which half is governmental funding. The background to the investment is that development within road transportation and Swedish automotive industry has big impact for growth. FFI will contribute to the following main goals: Reducing the environmental impact of transport, reducing the number killed and injured in traffic and Strengthening international competitiveness. Currently there are five collaboration programs: **Vehicle Development, Transport Efficiency, Vehicle and Traffic Safety, Energy & Environment and Sustainable Production Technology.**

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1. Executive summary

This project focuses on the development of a new generation of fasteners B14 with a significantly higher strength than the conventional fasteners 10.9 and 12.9 used today, i.e. the new fasteners have a target tensile strength higher than 1400 MPa combined meantime with satisfactory ductility.

Development of the new Ultra High Strength Steel (UHSS) fasteners is to meet increased demand for innovative application of fasteners for transport industry, to maximise efficiency on critical components like motor, to ensure safe and long-term operation, to reduce fastener material consumption, and to minimise CO_2 emission.

In the project tool design, cold heading procedures, heat treatment processes, design and simulation for construction joint, characterisation of mechanical properties of fasteners, tightening procedures and design guide lines will be simultaneously developed for the new fasteners. The new fastening technology and the performance of fasteners will be demonstrated and verified in Scania heavy trucks.

Three participants, two industrial companies, Bulten Sweden AB and Scania CV AB, and one research institute, Swerea KIMAB AB, have been jointly working with and operating the project. The project lasted two years, from 2011-03-01 to 2013-02-28.

The processes involved in production of UHSS B14 fasteners are cold heading, thread rolling and heat treatment. The project has showed that the material is well treated from wire drawing and has good performance in cold heading operation, even better than normal cold heading steel.

Original tooling have been used and worked as expected without any adjustment. Threading operation before hardening has been performed with standard thread rolling dies. Feedback from tests as tensile, fatigue and resistance for hydrogen embrittlement indicates so far no need of adjustment of radius in the thread profile.

In the heat treatment process this new material B14 requires higher tempering temperature, 600°C, compared to 450°C normally used for property class 10.9 materials. The parameters like tempering temperature, carbon potential and tempering lead time have been evaluated at different levels.

Mechanical properties at both ambient and/or elevated temperatures in terms of hardness test, tensile test, creep test, fatigue test as well as hydrogen embrittlement test for newly developed fasteners B14 are superior to these for currently used traditional fasteners 10.9 and 12.9. The mechanical testing data are also implemented into 2D finite element (FE) simulation and design to optimise fastener joints.

Properties and characteristic differences of fastener joints, with newly developed B14 and currently used 10.9, have been investigated with FE method in three different bulk materials, namely aluminium, grey cast iron and C70 steel. Four different thread engagement lengths are modelled in order to verify impacts of the thread engagement lengths. Results such as clamping force and its yield point are determined by extracting stress results from midsection of the joints. 80 % of the clamping force yield point for bolts is usually set as the limit of how much the joints can be tightened at most. The results showed that the B14 joints have ability of higher clamping force and tightening length compared to the 10.9 joints. FE analysis shows also that joints and bulk material reach material yield strength prior to the clamping force yield point. Most affected regions are the first thread, valid for both fasteners and bulk material, the transition section between head and shank of the bolt, and the most inner corner of the bearing surface.

It is expected that the new fastener technology developed in the present project will be implemented in Swedish vehicle industry and other industries which have a requirement or a competitive advantage of products with compact design and light weight.

2. Background

In a typical mid-size car there are approximately 2-3000 fasteners with different strength specifications. So many fasteners have a total weight of around 30kg. Applications of fasteners include in the body, dressing, chassis and drive line. The fasteners work in many cases at ambient temperature but in some engine applications temperature may go up to 500°C. Most of the fasteners today are based on conventional carbon steel for cold forging with a tensile strength of 800-1000 MPa. They are tightened by torque control which means that they are loaded well below their yield point.

Continuous development of ultra high strength steel (UHSS) makes it possible to produce new generation fasteners with a significantly higher strength than the conventional fasteners used today. The high strength fasteners have a great potential to considerably reduce weight and size of fasteners. In most cases the size of fastener can be lowered from e.g. dimension M8 to M6 or to even smaller. Not only the size of fasteners but also the clamping length can be reduced. This is the case for both ambient and elevated temperature applications. It is estimated that, with the new fastener technology, total weight of joints can be reduced by 28 kg, which corresponds to a reduction of CO_2 emission by 3g/km for a medium size car.

The new generation fasteners will be made of the fine grained, ultra clean, tempered martensitic steel B14 with a tensile strength higher than 1400 MPa. At this strength level the ductility of the material becomes critical. The steel B14 is a medium carbon steel, is quenched and tempered to martensite with a specially selected heat treatment. In order to reach the high ductility and to suppress sensitivity to hydrogen embrittlement ultra clean steel metallurgy has been utilized with very low contents of inclusions which have optimised compositions, shapes, sizes and 3D distributions. This is a unique type of material not previously used for fasteners.

To our knowledge no other materials of this type are on the market for fasteners. Some European competitors are known to develop 1400 MPa grade steel for fasteners. That material has however a different metallurgical concept and with lower ductility than B14.

It is a challenge to manufacture UHSS B14 fasteners to meet increasing demand from transport industry. Many questions and problems such as cold forming of fasteners, production and heat treatment procedure, fastener performance and assembly must be answered and solved before the B14 fasteners can be used in vehicle industry.

3. Objective

To produce new generation fasteners made of the UHSS steel B14, the objectives of the project are:

1. Development of cold heading sequences and toolings adapted to the new fasteners.
2. Optimisation of heat treatment procedures suitable for the new fasteners with different dimensions.
3. Characterisation of mechanical properties and hydrogen embrittlement of the new fasteners at both ambient and elevated temperature applications.
4. Development of fastener assembly, yield point tightening and guide lines for new designs.
5. Demonstration of a pilot application.

4. Project realization

4.1. Cold heading sequences and toolings

Using original tools for cold forging, cold heading sequences and toolings have been adopted to production of this new B14 fasteners. Original toolings have worked as expected without any adjustment.

Threading operation before hardening has been performed with standard thread rolling dies for all tested dimensions. Feedback from tests as tensile, fatigue and resistance for hydrogen embrittlement indicates so far no need of adjustment of radius in the thread profile.

Threading operation after heat treatment needs higher capacity in the thread rolling machine due to further increased hardness for B14 compared to 10.9 fasteners. Also tooling life is reduced for thread rolling dies when threading operation is performed after heat treatment. Nevertheless, the ductility for the B14 material is high in spite of increased hardness. This makes the post thread rolling operation possible when using standard thread rolling dies and parameters.

4.2. Heat treatment procedures

Optimisation of heat treatment processes for a range of B14 fastener dimensions is necessary. This new material B14 requires higher tempering temperature, 600°C, compared to 450°C normally used for property class 10.9 materials. To adjust the tempering temperature it reduces the time for use and productivity. This will be unfortunately reality until the volumes have reached higher levels or more capacity in the production line such as multiple furnaces.

To evaluate the applicability of the new heat treatment processes, a capability statistical value of Cpk>1,33 is needed for the tensile strength at minimum 1400 MPa for dimension M10 to M16. It has shown that the tensile strength has been reached for dimension M10 to M16. For M8-products the tensile strength has however not come up to the minimum even if the same heat treatment has been used. The material used for manufacturing B14 fasteners with different dimensions is from the same batch of ladle so the ability to heat treatment would be similar. Question why the M8 fasteners have lower tensile strength than other dimensions keeps still unanswered. It is therefore of great interest to have this in mind for future work.

The heat treatment requires new upset of the furnace for B14 fasteners due to higher tempering temperature. Therefore, capacity will be to some extent limited until new furnaces are available.

4.3. Mechanical properties and hydrogen embrittlement

Microstructural characterisation and hardness measurement on B14 fasteners are of common practice. Hardness profile on the fastener thread is essential to verify carbon depleted zone. These tests were performed at Bulten Sweden AB and at Swerea KIMAB.

Using standard specimen tensile tests at room and at elevated temperature have been performed according to valid standard. The tensile testing results are very important to ensure performance of fasteners exposed to high stress without sudden brittle failure. The tensile tests were conducted at Bulten Sweden AB and at Swerea KIMAB.

Fatigue properties for B14 M10 bolts have been evaluated at three mean stress values $\sigma_m=0.4\times R_m$, $0.7\times R_m$ and $0.9\times R_m$, respectively, where R_m is the tensile strength, and compared to those for 10.9 M10 bolts. Fatigue results are critical for long-term safe operation. Fatigue tests were carried out at Swerea KIMAB.

(a)

(b)

Fig. 1 (a) Instron test frame for tensile testing. (b) Fatigue test frame.

Creep tests using standard specimens at elevated temperatures up to 450°C have been conducted in accordance with relevant standard. Creep properties are critical for elevated temperature application and for long-term safe operation. Creep tests were carried out at Swerea KIMAB.

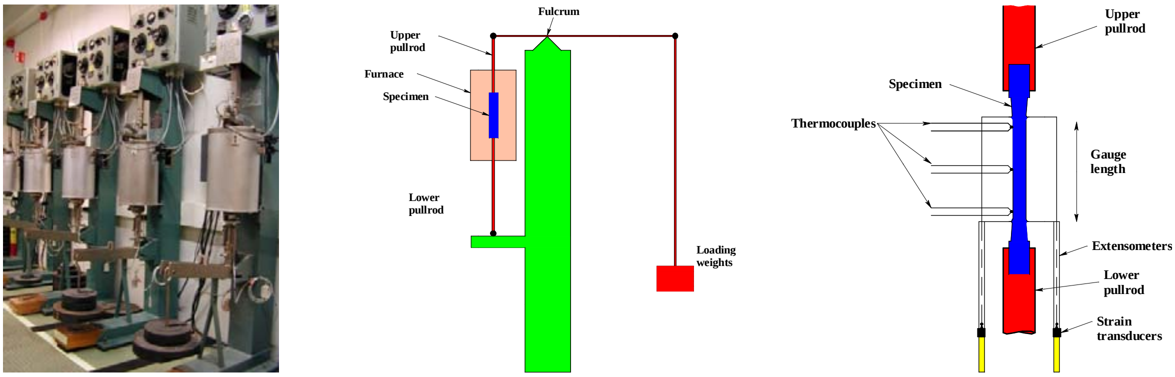


Fig. 2 Bofors creep test frame and assembly.

Three different tests have been performed to investigate hydrogen embrittlement on B14 M10 bolts. The tests include the test based on a Japanese method used, the constant stress test and the modified stress increase test. These tests were performed at Bulten Sweden AB and at Swerea KIMAB.

Fig. 3 Hydrogen embrittlement test by Japanese method. Assembly and failed bolt.

4.4. Development of bolt assembly, yield point tightening and guide lines for new designs

Finite element analysis was conducted in finite element solver ABAQUS Implicit for joints with 10.9 and B14 fasteners engaged in bulk materials like aluminium, grey cast iron and steel C70. Comparison of the clamping force and respective yield point has been examined. Local plastic deformation has been estimated and related to the thread engagement length. The guideline for tightening fasteners is given. This work was performed at Swerea KIMAB.

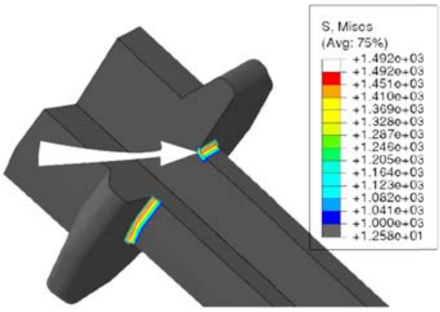


Fig. 4 Location of the initial plastic deformation in the fastener head region.

4.5. Demonstration of pilot application

A pilot application of B14 fastener in heavy vehicle was conducted to verify remaining clamping force under thermal cycles. The results were compared to traditional fasteners.

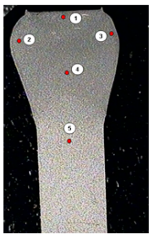
5. Results and deliverables

5.1. Results

It has showed that the material is well treated from wire drawing and has good performance in cold heading operation, even better than normal cold heading steel. The behaviour leads to flowing in a way that not creates any cracks when cold forging bolts, screws and studs. From cold heading operations the work hardening is starting from a hardness for the wire in the range of 200- 220 (HV0.3), see Fig. 5. After the 4^{th} blow the hardness has increased up to 310 (HV0.3) measured in axial direction from top of the head, see Fig. 6. The increase is depending of the degree of cold forming in different areas of a bolt. These figures are from a hexagon head bolt with flange where the degree of cold heading is quite big.

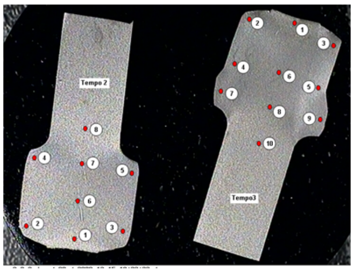
Measurements

HV0,3				Mätt ner från skalle, axiellt			
mm	TRÅD radiellt	TRÅD axiellt		1:a steg	2:a steg	3:e steg	4:e steg
0,05	205	200		308	287	295	313
0,1	212	210		313	295	300	304
0,15	218	217		304	283	284	295
0,2	217	210		294	278	278	285
0,25	215	213		284	266	275	280
0,4	220	220		255	248	245	259
0,5	223	216		249	236	230	248
1	226	222		224	211	203	215
				4 mm ner, radiellt skalle			
			0,05	259	243	257	260
			0,1	265	260	259	261
			0,15	267	270	260	266
			0,2	263	270	261	275
			0,4	267	263	260	267
			0,5	276	265	254	283
			0,7	275	279	251	278
			1	284	286	254	273
			1,5	278	284	250	270
			2	284	290	258	275
			3	283	282	264	276
			4	286	285	267	274
			5	297	287	265	279
			6	295	292	263	282

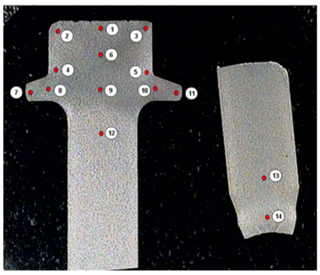


	HV0,3
1	249
2	283
3	285
4	264
5	233

Fig. 5 Hardness measurements on wire.



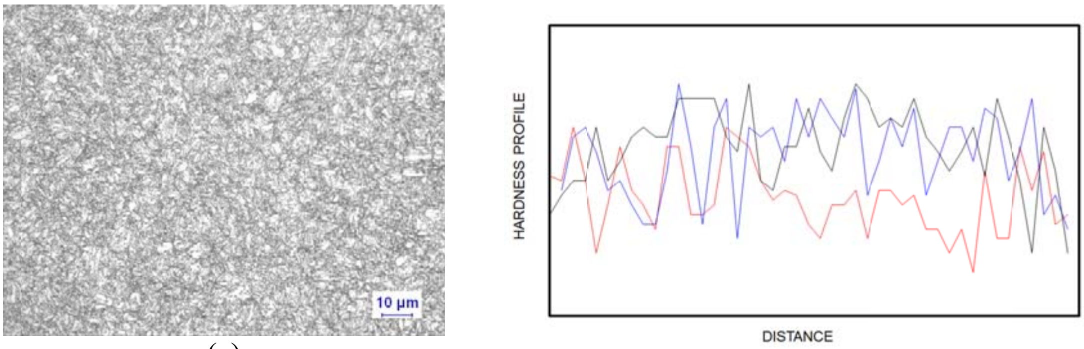
	Tempo2	Tempo3
1	238	213
2	268	257
3	278	251
4	272	268
5	271	275
6	269	271
7	213	280
8	231	271
9		284
10		232



	Tempo4
1	236
2	258
3	258
4	260
5	278
6	271
7	313
8	297
9	290
10	305
11	314
12	225
13	240
14	256

Fig. 6 Hardness measurements after cold forming steps 2-4.

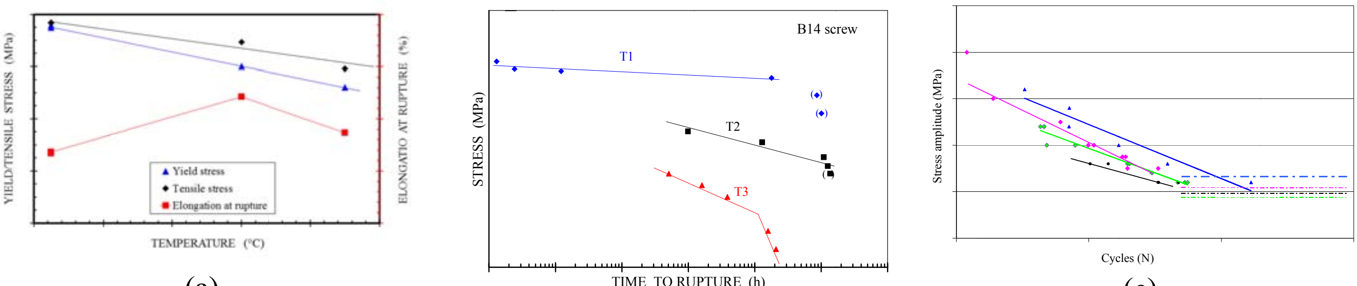
Brief summary of microstructural examination and mechanical testing results are given below. Microstructure of fine grained and tempered martensite and hardness profile are shown in Fig. 7, respectively. Microstructure and hardness profile are normal. Although the material is composed of tempered martensite with high hardness, the B14 fasteners are actually less sensitive to hydrogen embrittlement than the traditional ones. This has been verified by different testing methods.



(a) (b)

Fig. 7 (a) Fine grained and tempered martensite of B14 fastener. (b) Hardness profile.

Tensile, creep and fatigue properties are given in Fig. 8. Tensile strength decreases with increasing temperature, whereas ductility increases with slightly increasing temperature. Good creep properties are obtained even at elevated temperatures. Fatigue properties for B14 fastener are better than those for the traditional one.



(a) (b) (c)

Fig. 8 Mechanical properties of B14 fastener. (a)Tensile properties. (b) Creep properties. (c) Fatigue properties.

FE analysis indicates that the levels of the clamping force yield point are essential. Thus these levels are considered as guideline when tightening fasteners. The analysis also shows that 30% higher clamping force yield point are obtained when using the B14 fasteners compared to the traditional ones.

Application of B14 bolts has been conducted by checking clamp force variation at given time and at elevated temperature. The remaining clamp force for B14 bolt has been compared to that for 10.9 one at the same condition. The remaining clamp load is higher for B14 than that for 10.9.

5.2. Delivery to FFI-goals

Many activities and tasks have been carried out and completed to fulfil the objectives of the project. The output of the project has therefore contributed to

- Develop and produce new generation fasteners with ultra high strength and good ductility.
- Reduce fastener material consumption and make vehicle construction lighter.
- Reduce emissions of harmful acids and greenhouse gases.
- Improve efficiency of critical components and ensure safe operation.
- Develop tools and test methodology for sophisticate experiments and simulations.
- Generate useful and applicable results and methods.
- Optimise fastener joints for wide and advanced applications.
- Increase international competition and market share for Swedish vehicle industry.
- Gain key competence, know-how and experience for further development of next generation of fasteners.
- Increase contact between research institute, component producer and end user.
- Exchange and distribute knowledge, information and technology.

The results, FE analysis and testing methodologies of the project are also relevant to other industries like infrastructure, manufacturing and energy which fasteners joints are frequently used.

6. Dissemination and publications

6.1. Knowledge and results dissemination

The new generation B14 fasteners have been demonstrated to satisfy all the expected criteria. Therefore, the application of B14 fasteners can be commercialised and marketed through announcement on the Vinnova homepage. Actually, exchange of technological information and methodology transfer have continuously occurred between the project partners and shared with external researcher, manufacturer and end user in a seminar. In addition, the current project is relevant to a previous FFI project 'OptiFastening'. The project partners, Bulten Sweden AB, Scania CV AB andSwerea KIMAB AB, are co-founders of the SFN (Swedish Fasteners Network) for implementation of modern fastener joint technology in the Swedish vehicle industry.

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6.2. Publications

1. B14 - Ultra high strength and ultra clean steel for light weight fastener, Bulten Sweden AB, mötesplats för framgångsrika verkstäder!, Katrineholm, (2012)
2. Modelling 10.9 and B14 fasteners, report Swerea KIMAB, KIMAB-2012-116, (2012)
3. Creep properties of B14 fasteners at elevated temperatures, report Swerea KIMAB, (2013), in progress
4. Hydrogen embrittlement test 10.9, 12.9 and B 14, Bulten Sweden AB, Engineering report, 2012-08-R1, (2012)
5. Hydrogen sensitivity using a modified stress increase test (MSIT) method for three screw materials, report Swerea KIMAB, (2012)
6. Fatigue properties of UHSS B14 bolt, report Swerea KIMAB, KIMAB-2013-112, (2013)

7. Conclusions and future research

The present type of B14 fastener is unique internationally, not only its ultra high strength, but also its good ductility, the latter makes it distinguishing from competitor.

1. The most important achievements of the project are the capability of producing ultra high strength fasteners with satisfactory properties in an industrial scale and to test the fasteners joints used in vehicles. These make it possible to commercially introduce UHSS B14 fasteners into market.
2. New and useful data of mechanical properties like tensile, creep, fatigue and hydrogen embrittlement have been generated. These data can be utilized to simulate behavior of B14 fastener joints, to design shape and dimension of fasteners, and to ensure safe and long-term operation.
3. Using mechanical testing data, the 2D simulation has been performed to assess distribution of stress and strain in fastener joints. The assessment provides guideline for design for fasteners and joints.
4. Good agreement in amplitude of clamping force between theoretical simulation and practical trial is obtained for different grades of fasteners.
5. Different testing methodologies have been developed to meet special requirements.

Fastener joint has been playing and will constantly play an important role in construction of vehicles. However, performance of fastener joint is in many cases not maximally utilised to near yield strength clamping. To do this, better assembly method, comprehensive material data for advanced simulation and optimal design, continuous monitoring and control of fastener joints at mounting and during operation are necessary. Besides, development of new material and joint is everlasting. For instance, a European competing fastener material with tensile strength up to 1600 MPa is on the development. To meet increasing competition and demand, the following works are proposed for future:

1. Develop new and stronger material for fastener application.
2. Develop/upgrade new tooling system and heat treatment for production of new and stronger fasteners.
3. Develop/adopt 3D simulation tools for advanced and sophisticated assessment for distribution of stress and strain.
4. Develop/adopt/standardise test methodologies for better and deeper understanding of material mechanical behaviour at both room and elevated temperatures such as interaction of creep and fatigue, notch/thread sensitivity, hydrogen embrittlement, fracture mechanics, and mechanical behaviour combined with environment.
5. Study the effect of heat treatment, cooling speed, residual stress and surface finishing on mechanical properties of fasteners with different dimensions.
6. Implement new fastener technology in Swedish vehicle industry and other industries which have a demand or a competitive advantage of products with compact design and light weight.

8. Participating parties and contact person

Participating parties of the project are Bulten Sweden AB, Scania CV AB and Swerea KIMAB.

The present project leader is Kurt Andersson, Bulten Sweden AB. All the participants are listed below:

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