Performance improvement of shrink-fitted assemblies by surface strengthening

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Interference fits are widely used in engineering applications. Many methods have been tried out to improve the strength of interference fits by improving the quality of the mating surfaces. An experimental investigation was carried out to study the strength of the assemblies after ball burnishing the shafts, which improves the surface finish and also imparts the surface strength by way of improving the hardness and residual compressive stresses. The assemblies were soaked for different duration times at elevated temperature and then the axial load-bearing tests were carried out in a Universal testing machine. The surface strengthening of shafts by burnishing and ageing of assemblies at high temperature resulted in considerable improvement of strength of the interference fit assemblies. This paper discusses the experimental investigations in detail and analyses the strength obtained from them.

1 INTRODUCTION

Interference fitted assemblies are widely used in engineering practice because of their ability to withstand high loosening forces. The contact pressure between the mating surfaces is very high in these assemblies and so the surface finish and the material properties of the components play a vital role in deciding the strength of the assemblies. An improvement in the performance of the assemblies can be expected if the components are subjected to surface strengthening processes, which gives good surface finish and improves the surface characteristics. Again these assemblies when aged at elevated temperature for different periods can behave differently from normal assemblies. A series of investigations was made in order to understand the influence of burnishing the shafts, followed by ageing of assemblies at elevated temperature, on their ability to withstand an axial loosening force.

2 SURFACE STRENGTHENING PROCESSES

Methods of surface strengthening by induction hardening, roller (or ball) burnishing, vibration burnishing, etc., have gained wide acceptance for increasing the life of shafts in interference fits (**1, 2**). The fatigue and corrosion strengths of the surfaces through plastic deformation by roller (or ball) burnishing are improved considerably. Earlier experiments have shown that the use of a burnishing force higher than the optimum not only reduces the strengthening effect but also leads to the fatigue limit of the burnished parts dropping below that of an unburnished part (**1, 3**). High temperatures and pressures in the zone of interaction between the grains and heavy plastic deformation on the surface of the workpiece lead to substantial changes in the physical properties of the subject surface layer. At the same time, the asperities on the surfaces are merely sheared off, mainly in the transverse direction. The main feature of the surfaces of parts that are burnished is the displacement of the asperities and the smoothness of the surface. Application of permanent surface deformation through rollers (or balls) contributes to a greater hardness of the surface layer and the creation of residual compressive stress, which has a beneficial effect on the endurance of the parts (**3, 4**). The advantage of burnishing is the regularity of surface finish produced in the longitudinal and transverse directions, and the possible increase in the contact area of the parts and friction force between them. However, the effect of surface strengthening by rolling (burnishing) combined with strain hardening of the assemblies has not been sufficiently studied. Here investigations have been made to understand the effect of grinding and burnishing of mating surface shrink-fitted assemblies, followed by ageing at elevated temperatures, on their ability to withstand an axial loosening force.

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3 EXPERIMENTAL DETAILS

3.1 Specimen preparation

The shafts and the sleeves (Fig. 1a and b) were made of medium carbon steel and mild steel respectively. For the experiments 20H7u6 intereference was selected. However, for comparing the performance, components were selectively assembled to obtain an interference of 25 μm. Care was taken to eliminate parts, both bushes and shafts, that gave high roundness and taper errors. The shafts were finished by grinding and burnishing operations. Before burnishing, the shafts were ground in a cylindrical grinding machine. Long shafts were manufactured initially; after burnishing, they were cut to the required length. Burnishing of the shafts were carried out with burnishing loads of 20, 40 and 60 kgf. Burnishing loads were applied at one pass and no coolant was used. After grinding and burnishing of the components, surface residual stresses were measured using an X-ray diffractomer and the values obtained are given in Table 1.

Typical surface profiles of components after grinding and burnishing, used for load testing, are shown in Fig. 2. Burnishing was performed in a lathe, using a high-speed steel ball of 15.5 mm diameter held in a resilient spring holder (Fig. 3). Burnishing speed and feed were maintained in all cases. The burnishing load was measured using a three-component dynamometer (Fig. 4).

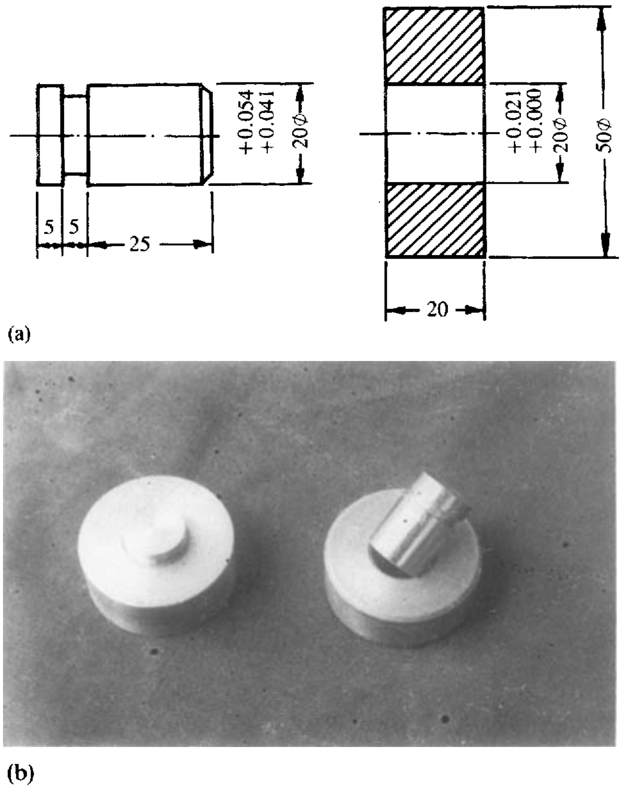


Fig. 1 (a) Dimensions of the parts used in the fit
(b) Shaft and bush, before and after assembly

Table 1 Measurements of surface residual stresses

Burnishing load	Residual stress (compressive)
kgf	kgf/mm^2
20	38.50
40	41.50
60	42.02

The bores of all the bushes were finished by internal grinding. Taper and out-of-roundness of the parts were also checked in addition to the surface finish. Typical roundness profiles of the components are shown in Fig. 5.

4 ASSEMBLY OF COMPONENTS

The shafts were cooled in liquid nitrogen for about five minutes and then assembled on to the bush freely without applying any external force. The assemblies were put in a muffle furnace at elevated temperatures of 300, 500 and 650°C for different soaking periods of 3, 5 and 7 h. After allowing them to cool completely in the muffle furnace itself, they were subjected to load testing in the Universal testing machine.

5 RESULTS AND DISCUSSIONS

Load–displacement curves obtained in the Universal testing machine are shown in Fig. 6a, b, c and d. The axial load-bearing strengths of the assemblies were plotted against ageing times for all the cases (Fig. 7a, b and c) and the results are presented in Table 2.

The preparation of the seating surfaces of parts of permanent joints by ball burnishing has an advantage over other machining methods such as reaming, jig boring, broaching and grinding. Results clearly indicate that smooth burnished surfaces ensure a substantially high load-bearing capacity of a joint over surfaces prepared by grinding and other operations (**5**). When the assemblies were subjected to elevated temperatures for short duration times of 3, 5 and 7 h the strength increased. This increase was maximum at 3 h of soaking and decreased as the ageing time was increased to 7 h. This is mainly due to an improvement in the quality of conjugate surfaces and the degree of work hardening caused by plastic deformation during ball burnishing followed by ageing at elevated temperatures.

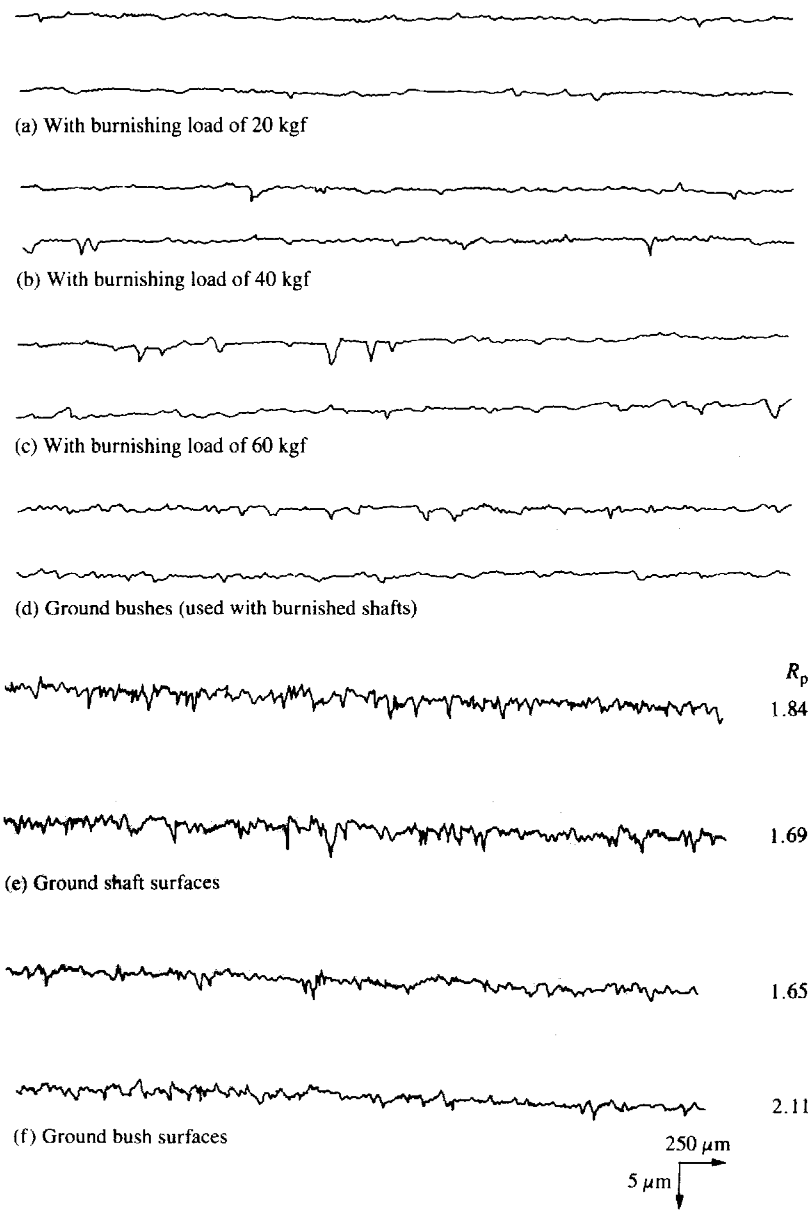
The results of the experiments after strengthening the shafts by burnishing indicate that, when they are soaked at high temperatures and low ageing times, the strength of the assemblies is high. The strength of the assembly reduces with further increases in the ageing period.

It is to be pointed out here that strain ageing is accelerated at higher temperatures. If the same temperature is maintained, it would be reasonable to conclude that the strain ageing would occur almost immediately at higher temperatures. When steel is cooled to room temperature it would exhibit all of the manifestations of strain ageing, that is an increase in hardness and tensile strength and a decrease in toughness. Metallurgists are not unanimous with regard to the temperature range at which this phenomenon occurs. It appears to depend on the alloy content and strain rate and occurs at higher temperatures when the strain rate is increased (**6–8**).

Here both the mating surfaces were subjected to high deformation due to grinding and burnishing operations which were likely to increase the dislocation density and which naturally led to interference in the dislocation movement when subjected to external load. Consequently this increases the strength of the metal. According to work done by Warrington (**5–6**) a lower yield stress of a material is determined by sub-grain size, and grain size plays no important role in determining the

Table 2 Axial load test results (with bush of mild steel and shaft of medium carbon steel)

Sample	Ambient condition	300°C			500°C			650°C		
		3 h	5 h	7 h	3 h	5 h	7 h	3 h	5 h	7 h
1. Ground shafts and ground bushes	3.10	6.65	8.20	6.00	7.50	7.45	6.20	8.95	5.30	5.80
2. Ground bushes and burnished shafts (burnishing load 20 kgf)	2.20	4.90	9.80	5.30	9.50	13.70	7.20	14.30	16.90	10.50
3. Ground bushes and burnished shafts (burnishing load 40 kgf)	3.20	9.30	9.80	7.90	8.40	13.00	7.60	17.20	19.05	15.00
4. Ground bushes and burnished shafts (burnishing load 60 kgf)	3.45	9.10	9.20	6.80	7.45	14.05	7.20	17.30	17.90	14.80



Profile	R_p	R_s	R_a	R_{max}	R_t	R_z
(a) With burnishing load of 20 kgf			0.17	2.68	2.68	1.72
			0.17	1.63	1.77	1.31
(b) With burnishing load of 40 kgf			0.18	2.18	2.93	1.64
			0.18	3.55	4.47	2.06
(c) With burnishing load of 60 kgf			0.23	3.48	3.48	2.01
			0.21	2.50	2.60	2.04
(d) Ground bushes (used with burnished shafts)			0.27	3.57	4.06	2.55
			0.22	2.13	2.13	1.76
(e) Ground shaft surfaces	1.84	0.58	0.45	4.36	4.70	3.93
	1.69	0.65	0.50	5.37	5.53	4.38
(f) Ground bush surfaces	1.65	0.42	0.34	3.88	3.88	2.90
	2.11	0.44	0.34	3.28	4.07	2.98

Shaft: medium carbon steel
Bush: mild steel

Fig. 2 Typical surface profiles of components used for load testing

flow stress. Perhaps the most general method of producing a sub-structure network is by introducing a small amount of deformation and following it with an annealing treatment to rearrange the disclocation into sub-grain boundaries. The amount of deformation and temperature must be low enough to prevent the formation of new grains by recrystallization (**6, 7**). The formation of sub-grains in an annealed material results in a

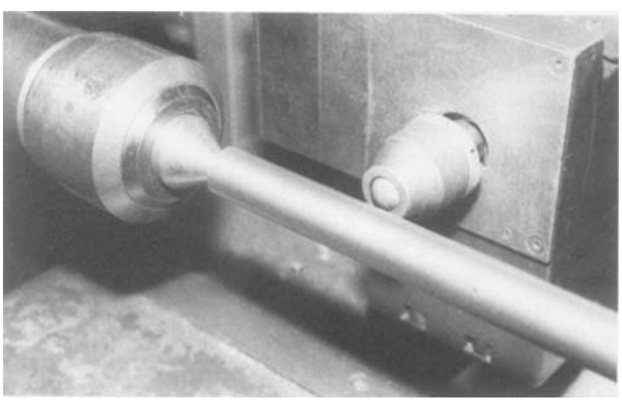


Fig. 3 Set-up showing the burnishing tool and the workpiece

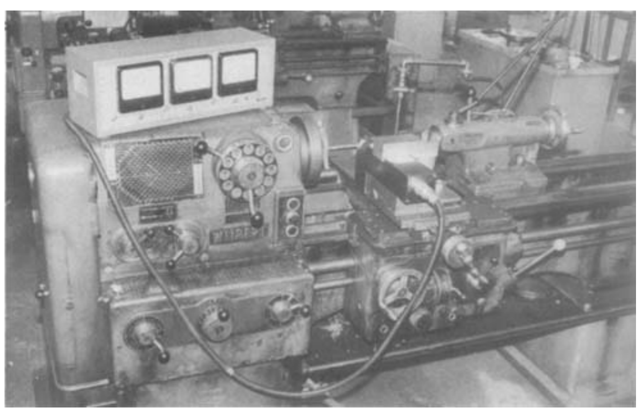


Fig. 4 Set-up showing lathe with dynamometer used for burnishing the shafts

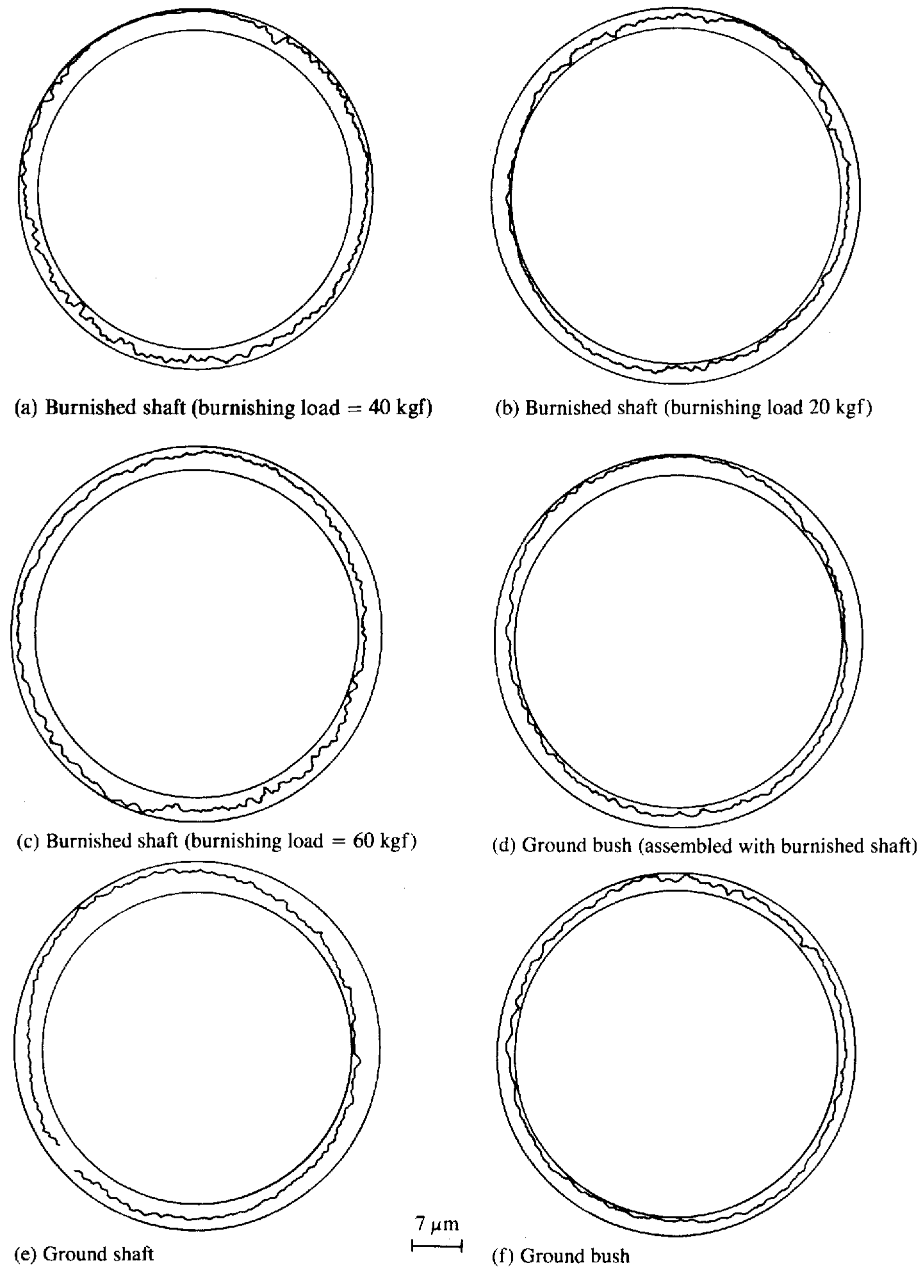
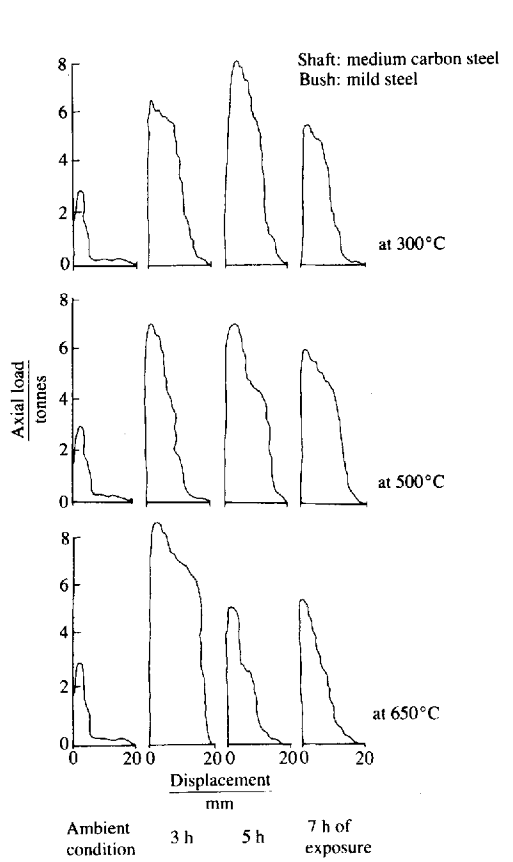


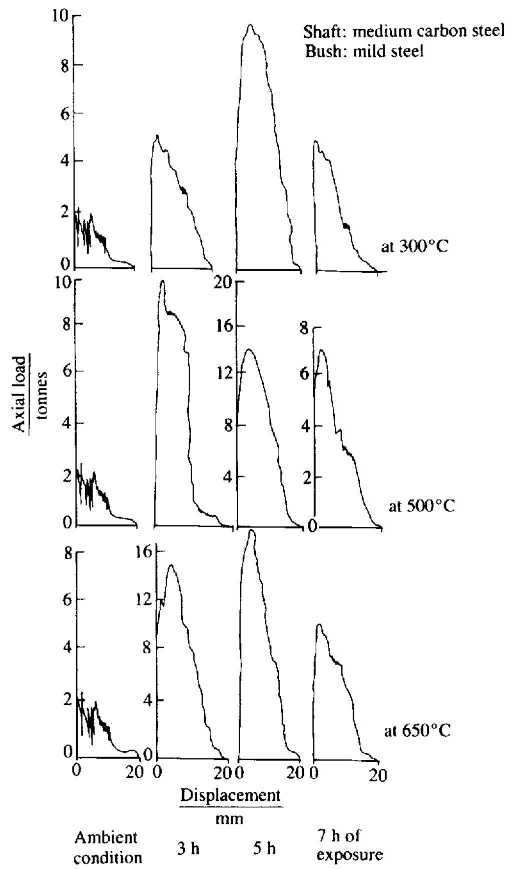
Fig. 5 Typical roundness profiles of bushes and shafts used for load testing

significant increase in strength. This increases the yield strength due to an increase in the density of sub-grain boundaries produced by various prestraining and annealing treatments. With further ageing (7 h of soaking), the particles or precipitates, such as carbon and nitrogen atoms, in the grain boundaries lose their coherency, leading to a decrease in the yield strength. Such a loss of coherency with an increase in the ageing period is reported by Guiner and Preston (**6**, **8**) and was detected by special X-ray techniques.

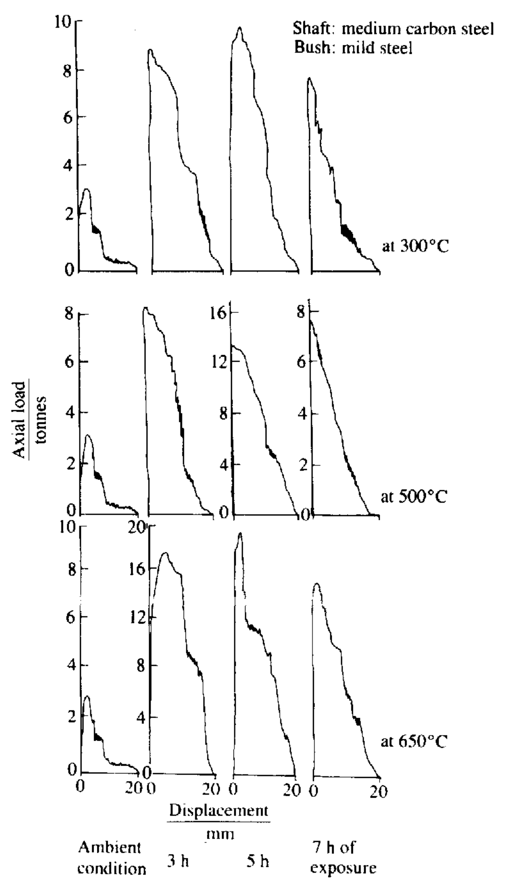
Nitrogen also plays an important role in the strain ageing of iron because it has a high solubility and diffusion coefficient and produces less complete precipitation during slow cooling. Generally carbon-dependent ageing processes also contribute to the hardness through precipitation hardening. Some of the strongest alloys are produced by combining the effects of precipitation and strain hardening (**7**). If plastic deformation precedes the ageing treatment, a finer dispersion is produced when particles nucleate on the dislocations in the matrix. The strongest alloys seem to be those in which particles are formed in dense dislocation cell structures in the deformed matrix. Extensive plastic deformation of alloys containing fine, strongly dispersed particles can result in very high strength. This phenomenon could therefore be responsible for a higher load-bearing capacity by increasing the strength, particularly on the surface at the interface of the assemblies, at elevated temperatures with lower ageing times and by decreasing the strength with further ageing times. The increase in the strength of the assemblies soaked at elevated temperatures (500 and 650°C) indicates the other possible reasons for this effect apart from strain ageing. An oxide layer formation can be expected at the interface of the mating components which is a diffusion-related phenomenon. Here again, the oxide layer formation is a kinematic reaction, dependent on time and temperature. The oxide layer between the components of the joint



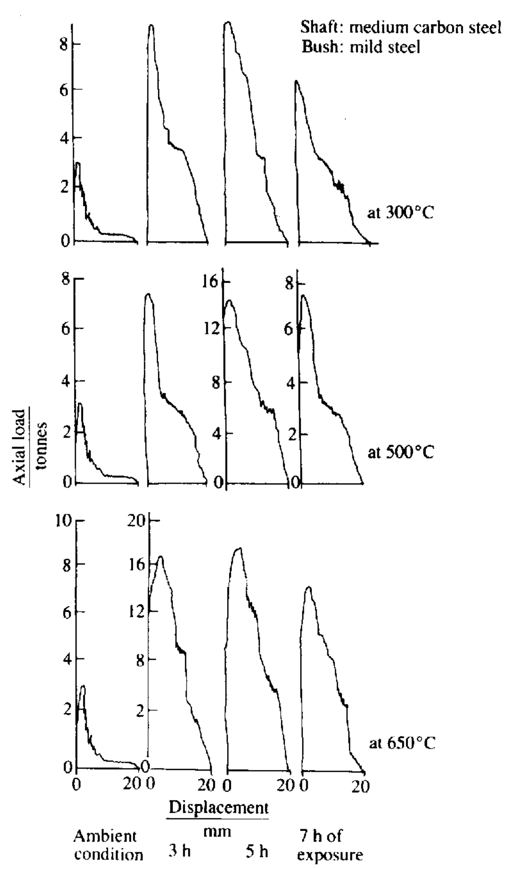
(a) Ground shafts and ground bushes



(b) Ground bushes and burnished shafts (burnishing load = 20 kgf)



(c) Ground bushes and burnished shafts (burnishing load = 40 kgf)



(d) Ground bushes and burnished shafts (burnishing load = 60 kgf)

Fig. 6 Load–displacement curves

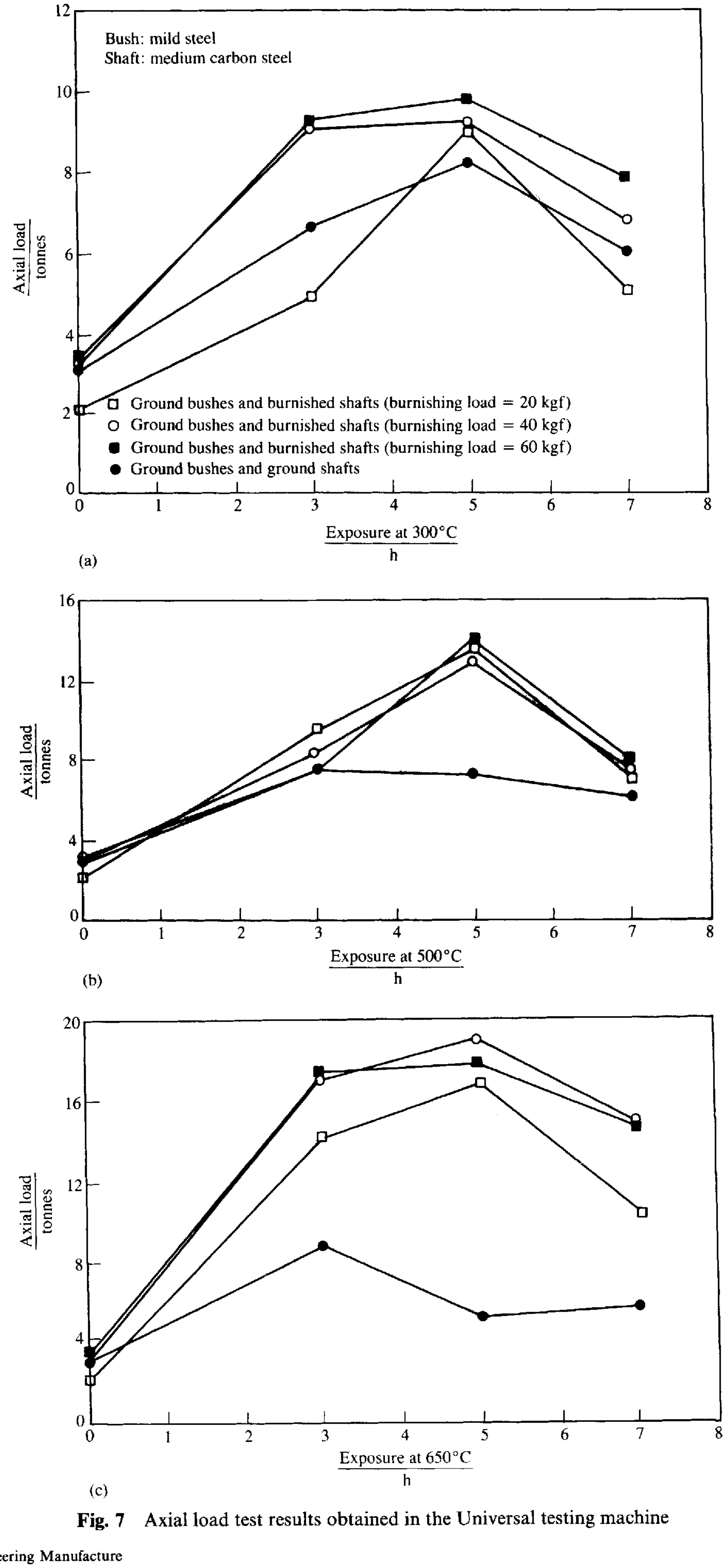


Fig. 7 Axial load test results obtained in the Universal testing machine

would result in increased compressive residual stresses due to 'oxide jacking' and this could account for the higher axial loads withstood by these assemblies. The residual compressive stresses are likely to be relieved at longer soaking periods (7 h) at elevated temperatures and contribute to the reduction in strength as shown in Fig. 7. The failure of the stainless steel shaft/medium carbon steel assembly at lower loads (5) strengthens this argument since stainless steel is inert to strain ageing and oxidation, particularly where there is no carbon and nitrogen content.

6 CONCLUSIONS

Significant surface strengthening through plastic deformation of parts is obtained by ball burnishing, which also smoothes the initial irregularities produced by machining operations. Burnishing of seating surfaces has an advantage over other machining methods such as grinding, jig boring, reaming and broaching, and ensures a substantially high load-bearing capacity of a shrink-fitted assembly.

The creation of an optimum microgeometry of the surfaces by burnishing provides the maximum load-bearing capacity for a joint, which by means of finish machining based on cutting is complicated in many other cases and is sometimes impossible.

The application of permanent deformation through ball burnishing contributes to a greater hardness of the surface layer and the creation of compressive residual stresses in it. When the assembly is subjected to ageing at elevated temperatures with these primary effects, there is definitely a beneficial effect on the strength of the joints. The strength or the load-bearing capacity of the joints increase by nearly five times under these conditions compared to normal assemblies. This is true for medium carbon steel and mild steel as shaft and bush materials respectively.

REFERENCES

1 **Belkin, L. M.** Surface strengthening of plane parts by plastic deformation. *Soviet Engng Res.*, 1984, **4**(9), 30–31.
2 **Pogoretskii,** Strengthening methods for press fit shafts effectively increase fatigue and corrosion strength. *Russ. Engng J.*, 1974, **54**(10), 73–75.
3 **Ramamoorthy, B.** and **Radhakrishnan, V.** Effect of burnishing of shafts on the performance of interference assemblies. Proceedings of Thirteenth AIMTDR Conference, Jadavpur University, 1988, pp. J13–J16.
4 **Shneider, Yu. G.** and **Zabrodin, V. A.** Strength of permanent joints of parts with a regular micro-finish. *Russ. Engng J.*, 1976, **56**(6), 37–38.
5 **Ramamoorthy, B.** and **Radhakrishnan, V.** Improving the load carrying capacity of interference fits. *Proc. Instn Mech. Engrs*, Part B, 1989, **203**(B2), 83–90.
6 **Cahn, R. W.** *Physical metallurgy*, 1970 (North-Holland, Amsterdam and London).
7 **Rajendrakumar** *Physical metallurgy of iron and steel*, 1968 (Asia Publishing House).
8 **Dieter, G. E.** *Mechanical metallurgy*, 1976 (McGraw-Hill).